FINAL REPORT

Title: Effectiveness of Joint Fuel Treatments and Vegetation Management in Restoring Eastern Upland Oak Ecosystems

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List of Abbreviations/Acronyms

AS – advanced savannas thinned to 7 m^2 ha^{-1} residual basal area and burned biennially 8 times

CCA – canonical correspondence analysis

CWF – coarse woody fuel, an aggregation of 10, 100, and 1000 hour fuel-loading

CWMA – Catoosa Wildlife Management Area, Tennessee Wildlife Resources Agency

FaO – fall burn-only forest stands

FaS – forest stands thinned to savanna residual basal area (7 m^2 ha^{-1}) and fall burned

FaW – forest stands thinned to woodland residual basal area (14 m^2 ha^{-1}) and fall burned

FWF – fine woody fuel, an aggregation of litter and 10 hour fuel-loading

GRGL – Green River Game Lands, North Carolina Wildlife Resources Commission

LBL – Land Between the Lakes National Recreation Area, United States Forest Service

Mid-South – Southern Appalachian and Central Hardwood regions defined by Harper et al. (2016)

MRT – multivariate regression tree analysis

SpO – spring burn-only forest stands

SpS – forest stands thinned to savanna residual basal area (7 m^2 ha^{-1}) and spring burned

SpW – forest stands thinned to woodland residual basal area (14 m^2 ha^{-1}) and spring burned

Keywords

shortleaf pine; warm-season grass; fire suppression; woody encroachment; fire season; canopy disturbance; shortleaf-bluestem; restoration; Tennessee; fuel treatment; thinning; prescribed fire; fire season; herbaceous fuel; mesophication; oak regeneration; North Carolina; woody encroachment; savanna; and woodland.

Acknowledgements

We thank the Joint Fire Science Program (Project ID: 13-1-04-14), University of Tennessee (Department of Forestry, Wildlife, and Fisheries), and Tennessee Wildlife Resources Agency (TWRA) for financial support of this research. We thank TWRA (at CWMA), the North Carolina Wildlife Resources Commission (NCWRC at GRGL), and the U.S. Forest Service (at LBL) for implementing treatments and providing field-season housing. We specifically thank TWRA staff M. Lipner, C. Kilmer, and C. Coffey (retired), U.S. Forest Service Staff D. Wilson and R. Lomax, and NCWRC staff. We also acknowledge numerous field technicians for assistance with data collection; P. Acker, C. Ault, L. Brinkman, J. Clark, E. Clarkson, M. Cox, M. Critean, K. Dreyer, T. Duke, C. Gresham, K. Goostree, R. Hunter, A. Jackson, A. Lambert, J. Lippert, K. McCoy, J. Myers, F. Nebenburgh, J. Orange, J. Redden, S. Snow, D. Stamey, C. Swafford, J. Tapp, J. Trussa, W. Underwood., S. White, and B. Whitley. Without the assistance of these individuals, this work would not have been possible.

Abstract

Removing fire's influence from Southern Appalachian and Central Hardwood forests (Mid-South) has 1) virtually eliminated communities defined by shortleaf pine (*Pinus echinata*) and native warm-season grasses, 2) greatly altered fuel-bed properties, 3) limited the regeneration of shade-intolerant and fire-adapted woody species, and 4) decreased herbaceous groundcover and diversity. We evaluated the ability of canopy-disturbance (none, 7, and 14 m^2 ha^{-1} residual basal area) and fire-season (none, October, and March) combinations to reverse such trends by monitoring vegetation and fuels from 2008 to 2016 at three sites located across the Mid-South. Shortleaf pine regeneration and native warm-season grasses occurred when canopy closure was reduced below 65 % and the dominance of understory woody vegetation was reduced. Regardless of degree, thinning doubled (+19.6 Mg ha^{-1}) coarse woody fuels (diameter >0.66 cm) and 3 biennial fires did not affect this difference. A net reduction of fine-fuels (reduced woody [litter and 1-hour], increased herbaceous) followed thinning and burning; however, maintenance required biennial burning, and the rate of herbaceous fuel increase suggested future compensation for observed reductions in fine woody-fuels. Thinning and fire shifted understory woody communities towards shade-intolerant and fire-tolerant woody species. Management nearly doubled (+2,256 stems ha^{-1}) oak (*Quercus* spp.) seedling density across all sites, but persistent mesophytic species (largely red maple [*Acer rubrum*]) limited response. Increases in herbaceous diversity from pre- to post- management across sites ranged from 3.4- to 5.2- fold. Across all monitoring, the effects of fire-season were not strong. Our results question restoration associated thinning and burning as regionally effective treatments, but demonstrate that disturbance increases the diversity, function, and sustainability of regional forest communities.

Objectives

This project addresses Task Statement 4: "*Fuels treatment effectiveness: Ecosystem restoration*" of JFSP Project Announcement FA-FON0013-0001. Our overall goal was to assess the effectiveness of canopy-disturbance (none, 7, and 14 m^2 ha^{-1} residual basal area) and fire-season (none, October, and March) combinations as fuel and restoration treatments within Southern Appalachian and Central Hardwood forests. Effective fuel treatments were defined as those reducing the loading (Mg ha^{-1}) of fine-fuels (litter, 1-hour, and herbaceous), which drive fire-behavior, and coarse fuels (10, 100, and 1000 hour fuels), which influence wildfire severity. We focused our evaluation of restoration on 1) the promotion of shortleaf pine (*Pinus echinata*) regeneration and native C_4 grasses (shortleaf-bluestem community components), 2) the reversal of mesophication effects on understory woody vegetation, and 3) increases in herbaceous groundcover and diversity. We had the following specific hypotheses:

Shortleaf-bluestem community restoration: Simultaneous promotion of shortleaf pine regeneration and native C_4 grasses would involve multivariate relationships between canopy openness, reduced woody density in the understory, and site conditions conducive to restoration (*e.g.*, xeric aspects, proximity to overstory shortleaf).

Fuel-dynamics: Thinning would increase coarse woody fuel (CWF – 10, 100, and 1000 hour) loads, subsequent fire would reduce CWF and fine woody fuel (FWF – litter and 1 hour) loads, and the drier conditions associated with March (vs. October) burning would lead to greater fuel reductions. Herbaceous fuel loads would increase and compensate for FWF loss.

Understory woody vegetation: The density of shade-intolerant woody species would increase with increasing canopy disturbance, and burning would promote fire-tolerant woody species. Repeated fire prior to leaf-abscission (October) would result in greater reductions in understory woody density than fire conducted prior to bud-break (March). Canopy disturbance and fire-season would interact such that heavy thinning and October fire would result in the greatest reversal of mesophication effects on understory woody communities.

Herbaceous groundcover and diversity: Increases with increasing canopy disturbance, but a peak in diversity at intermediate overstory density. Fire applied prior to leaf abscission (October) would result in greater reductions in woody groundcover, and, therefore, greater increases in herbaceous metrics, than fires occurring prior to bud-break (March). Herbaceous groundcover and diversity would be best promoted by heavy thinning and October fire.

Background

Removing fire from its historical role in shaping oak (*Quercus* spp.) and pine (*Pinus* spp.) community development throughout the Mid-South (Abrams 1992; Guyette et al. 2007) has yielded a multiplicity of negative effects (Nowacki & Abrams 2008). The remnants of this legacy are vanishing as shortleaf pine and oak overstories approach senescence (Abrams 2003; South & Harper 2016). Shortleaf-bluestem communities, defined by a sparse overstory of shortleaf pine and robust native C_4 grass groundcover, have been virtually eliminated east of the Mississippi River (NatureServe 2013; Anderson et al. 2016). Decreased fuel-bed flammability threatens restoration success even where fire is reintroduced (Nowacki & Abrams 2008). Mesophication has promoted dark, moist, and cool micro-environments dominated species with physical and chemical leaf-litter (hereafter, litter) properties not conducive to fire (Kreye et al. 2013; Alexander & Arthur 2014; Varner et al. 2015). Alternatively, accumulating heavy fuels, climate-change, and associated increases in fire activity (Mitchell et al. 2014) could combine to promote catastrophic wildfires that degrade regional ecosystems (Vose & Elliott 2016). Regeneration cohorts of shade-intolerant and fire-tolerant woody species have been rendered non-competitive by the extended absence of disturbance (Oswalt 2012; Brose et al. 2014). Understories once dominated by a lush diversity of native grasses, forbs, and legumes have been reduced to continuous leaf litter through light reductions and resource gradient eliminations (Hutchinson et al. 2005; Lettow et al. 2014).

Addressing altered fuel dynamics while restoring the composition, structure, and function of some of the most imperiled terrestrial communities in North America (Nuzzo 1986; Noss et al. 1995) will involve the return of appropriate disturbance regimes. Canopy disturbance and fire promote shortleaf pine regeneration and C_4 grasses, the key components for sustaining shortleaf-bluestem communities (Stambaugh et al. 2007; Maynard & Brewer 2013). Such restoration alters fuel-beds and increases their ability to support a long-term regimen of repeated fire, which increases CWF consumption (Fernandes & Botelho 2003) and decreases smoke emissions (Goodrick et al. 2010) and wildfire risk (Stambaugh et al. 2011). In conjunction, canopy disturbance and fire can reverse mesophication effects by shifting composition toward shade-intolerant and fire-adapted species (Iverson et al. 2017; Vander Yacht et al. 2017). Canopy-disturbance increases the light available for herbaceous germination and growth (Nielsen et al. 2003; Brewer 2016), and a long-term regimen of biennial fire can maximize herbaceous groundcover and diversity by suppressing woody competition (Peterson et al. 2007; Peterson & Reich 2008).

Despite this knowledge, our understanding of how to efficiently and accurately correct altered fuel and vegetation dynamics remains limited. Specifically, knowledge gaps involving recommended overstory reduction rates (Jackson et al. 2006), fire-season effects (Knapp et al. 2009), and the tracking of long term management results require attention. Most knowledge regarding shortleaf-bluestem communities comes from west of the Mississippi river (Anderson et al. 2016). Applying this information in the east, where less research has occurred with disappointing (Elliott et al. 2012), is complicated by differences in climate, length of fire suppression, presence of remnant shortleaf pine, and hardwood competition. Fuel-treatments have been understudied and ineffective in the Mid-South (Waldrop et al. 2016), and long-term evaluations often lack canopy-disturbance (Arthur et al. 2017). Also, the contributions of herbaceous fuels to have been largely ignored. Recent evaluations of repeated fire on woody vegetation in the Mid-South have not occurred in conjunction with canopy disturbance (Hutchinson et al. 2012; Arthur et al. 2015; Keyser et al. 2017). Growing-season fire can result in comparatively greater woody plant mortality and herbaceous layer gains than traditionally used dormant-season fire (Knapp et al. 2009). This could increase its use, but the effects of such a transition on fuels and vegetation has not been documented in the Mid-South.

Before investing additional resources into joint vegetation management and fuels treatments, it is imperative that effective management options are identified. We monitored fuel and vegetation response from 2008 to 2016 within a replicated experiment at three sites located across the Mid-South. Treatments evaluated included combinations of canopy disturbance (none, 7, and 14 m^2 ha^{-1} residual basal area) and prescribed fire-season (None, October, and March). Our goal was to elucidate management capable of efficiently restoring the fire-dependent components of oak and pine communities while reducing fuel loading to levels indicative of reduced wildfire risk and severity.

Materials and Methods

Study Areas

Our research occurred at 3 sites located across the Mid-South. Catoosa Wildlife Management Area (CWMA) is a 32,374 ha property managed by the Tennessee Wildlife

Resources Agency on the Cumberland Plateau in the Southwestern Appalachians ecoregion. Land Between the Lakes (LBL) is a 68,797 ha National Recreation Area in western Kentucky and Tennessee managed by the U.S. Forest Service and situated in the Western Highland Rim of the Interior Plateau. Green River Game Lands (GRGL) is a 5,726 ha North Carolina Wildlife Resources Commission property situated at the interface between the Blue Ridge and Piedmont ecoregions. The overstory at all sites was dominated by oaks and a minimal pine component. For a detailed description of each of these sites, please see the attached dissertation document.

Experimental Design and Restoration Treatments

We treated sites as independent experiments because of differences in species composition, the timing and type of management, and discontinuity of data collection. At each site, 20-ha forested stands (experimental unit) were configured to maximize core area and assigned a treatment using a completely randomized design. Treatments implemented included: 1) unmanaged (Control), 2) thinned to woodland residual basal area (14 m^2 ha^{-1}) and burned during spring (SpW), 3) thinned to woodland residual basal area and burned during fall (FaW), 4) thinned to savanna residual basal area (7 m^2 ha^{-1}) and burned during spring (SpS), and 5) thinned to savanna residual basal area and burned during fall (FaS). At LBL, all prescribed fires were conducted in spring (no FaS, FaW) including an additional treatment: 6) burn-only during spring (SpO). Target residual basal area for savannas at LBL was greater (9 m^2 ha^{-1}) than at other sites due to administrative constraints. At GRGL, we included 7) burn-only in the fall (FaO, in place of SpO). Treatments were replicated twice at CWMA, four times at LBL (except only 2 replicates of SpO and Control), and once at GRGL. For shortleaf-bluestem response, which was only monitored at CWMA, we also included advanced savannas (AS) burned eight times since 2000.

Canopy reductions were completed commercially during the dormant season (Fig. 1). Oaks, hickories (*Carya* spp.), and shortleaf pine were retained while fire-intolerant species (*e.g.*, *Acer* spp., *Liriodendron tulipifera*, and *Liquidambar styraciflua*) were removed. Ring firing was used at CWMA to burn FaW and FaS 3 times in mid-October prior to bud-break (2010, 2012, and 2014), and SpW and SpS 3 times in mid-March prior to leaf abscission (2011, 2013, and 2015). Similar seasonal timing of fire (October 2015 and March 2016) was applied once using strip-head firing at GRGL. At LBL, half of both SpW and SpS replicates and all SpO replicates were burned using strip-head firing in late April, 2015. Remaining SpW and SpS replicates were burned in late March, 2016 using aerial ignition from a helicopter. These latter stands were also burned in November of 2009 prior to canopy disturbance.

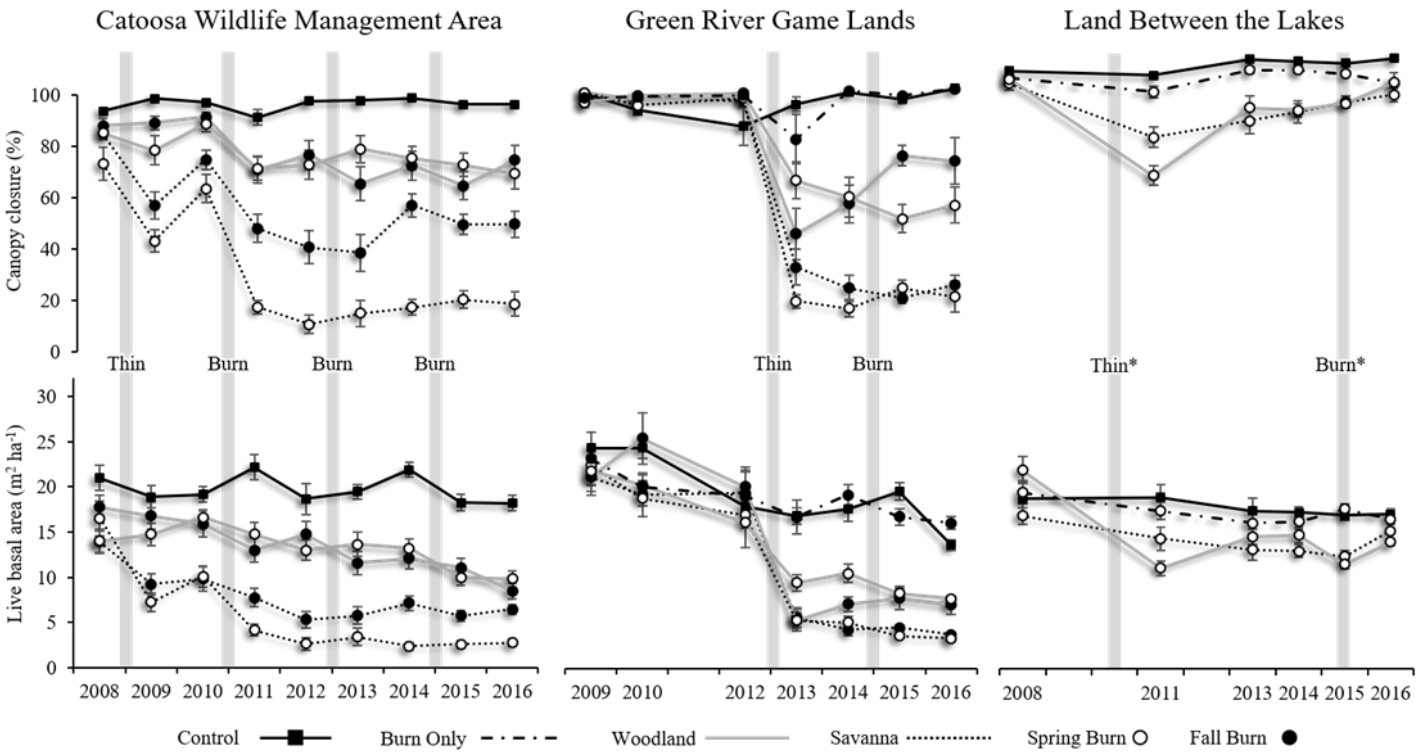

Fig. 1. Depiction of treatment implementation effects on canopy closure (%) and live tree basal area (m^2 ha^{-1}) during (2008 to 2016) oak woodland and savanna restoration experiments at 3 sites located across the Mid-South. Treatments included canopy disturbance (THIN) and prescribed fire in the fall (Fa) or spring (Sp).

Burning conditions and fire behavior were monitored similarly at all sites following Vander Yacht et al. (2017). This included oven drying fuel samples to determine moisture content, on-site weather recording, and systematic measurements of fire spread and flame lengths. We also sampled fire temperature using foil-wrapped ceramic tiles (n = 181) painted with Tempilaq® indicating liquids and placed at fuel sampling points (70 × 70 m grid). Burning conditions and fire behavior variables were generally consistent by season across sites. For simplicity, we present combined data for burning condition and fire behavior variables for all sites by season (Appendix D). Conditions were warmer (+7˚ C) and less windy (-1.9 m s-1), and fine-fuels (litter and 1-hour twigs) were nearly 5% drier, during fall relative to spring burning. However, heading fires in spring had nearly double the rate-of-spread and flame length of those in fall. Spring fires also burned nearly 40 ˚C hotter, on average, than fall fires.

Sampling Design and Data Collection

Data collection occurred from 2008-2016 in late May though early August, and included sampling within all management intervals at all sites (Fig. 1). We systematically located permanent plots (n = 15 $stand^{-1}$) along a 70 X 70 m grid (Avery & Burkhart 2002) within the core (50-m buffer) of each stand. Live tree basal area, dead tree basal area, canopy closure, percent slope, aspect, and slope position were measured at each plot. We measured basal area using a 2-factor, metric prism, and canopy closure using a convex spherical densiometer. A clinometer determined percent slope, and plots were assigned a numerical slope position value (1-6, corresponding to alluvial, cove, toe-slope, mid-slope, shoulder, and ridge).

Data used in evaluating shortleaf-bluestem community response to implemented management was collected in a similar fashion as the methods related to woody and herbaceous community monitoring, which are described below. Please consult chapter 1 of the included dissertation for a full account of all data collection contributing to this multivariate assessment. We monitored the loading of dead and down woody fuels (1, 10, 100, 1000 hour classes) using >60,240 m of planar-intercept transects (Brown 1974). Fine-fuels, including litter and herbaceous vegetation, were monitored using 6,300 collected and oven-dried samples. Please consult chapter 2 of the included dissertation for a detailed presentation of plot design, data collection, and fuel-load calculations.

Understory woody vegetation was surveyed at each plot in seven nested 1-m^2 and 3-m radius sub-plots at each plot. Within 1-m^2 sub-plots, stems of all seedling and shrubby vegetation were tallied by species. Seedlings were tree species (typically ≥4 m in height at maturity) ≥30.5 cm tall but <1.4 m tall. Shrubby vegetation included woody and semi-woody (largely *Smilax* and *Rubus* spp.) species that were typically multi-stemmed and rarely >4 m tall and lianas. Within 3-m radius sub-plots, we tallied sapling stems by species. Saplings were defined as stems of tree species ≥1.4 m tall and <7.6 cm DBH. Please consult chapter 3 of the included dissertation for a detailed presentation of woody plant community monitoring.

The point-intercept method (Bonham 1989) was used to collect data pertaining to herbaceous groundcover and diversity along a 50-m transect running through each plot location. At 1-m intervals, we categorized cover below a height of 1.37 m as either woody (tree and shrub species), litter, debris (down woody material >7.6 cm in diameter), bare, graminoid, forb, or fern. All intersected herbaceous vegetation was identified to species. We calculated percent groundcover for each category as the number of intercepts where a category was present divided by the total number of intercepts (50). We used these data to determine plot-level herbaceous richness and diversity using Shannon-Wiener’s Index (H′, Magurran 1988).

Data Analysis

For a full account of analyses, please consult the included dissertation. Shortleaf-bluestem response and explanatory variables were subjected to canonical correspondence (CCA) and multivariate regression tree (MRT) analyses to explore multivariate relationships, effect hierarchies, and associated thresholds in effects. We then examined differences in identified response groups using ANOVA and zero-inflated negative binomials. For fuel and herbaceous response evaluation, separate mixed-effect ANOVA models were developed for each dependent variable. Fixed-effects included treatment, year, and treatment × year interactions. Year was a fixed-effect because treatments were applied over time. Random-effects included replicates within a treatment and replicates within a treatment and year.

For fuel and herbaceous response ANOVA models, we expected results to often involve difficult to interpret treatment × year interactions because treatments were applied over time. Therefore, we used orthogonal contrasts to test specific, a priori hypotheses. We included treatment contrasts that tested for differences within specific management intervals (e.g., post-thin and pre-burn) and interaction contrasts that tested for differences across each available year interval (e.g., control versus treatment from 2009 to 2010). Comparisons included unmanaged to thinned (C vs. T), unmanaged to burned only (C vs. FaO and C vs. SpO), unmanaged to thinned and burned (C vs. TB), woodland to savanna residual basal area (W vs. S), and October to March burns (Fa vs. Sp). Except for C vs. T, which was always tested, contrast evaluation followed the implementation of the management action being compared. These analyses were conducted in SAS 9.4 using PROC MIXED (SAS Ins., Cary, N.C., USA).

We evaluated differences in shrubby, seedling, and sapling vegetation across treatments and time using restricted, non-parametric, and permutation-based multivariate analysis of variance (PERMANOVA, Anderson 2001). This analysis was conducted in RStudio version

1.0.143 (2016, RStudio, Inc., Boston, MA). Identified differences were visualized using non-metric multidimensional scaling (NMDS, Kruskal 1964). Indicator species analysis (Dufrene & Legendre 1997) and univariate mixed-effect analysis of variance (ANOVA) identified the species driving observed differences in woody vegetation across treatments and time. Finally, structured additive regression (STAR, Umlauf et al. 2015) was used to relate observed patterns in woody vegetation change to gradients in overstory and understory density.

Results and Discussion

Shortleaf-Bluestem Community Response

In descending importance, canopy closure, woody understory density, and site characteristics influenced the occurrence of shortleaf-bluestem community components (Fig. 2 and 3). The top 3 CCA axes explained 91.5 % of constrained variance and ordinated control plots far from any association with shortleaf-bluestem community components (Fig. 2). Response was negligible where canopy closure, vertical woody understory cover, and woody groundcover exceeded 65, 48, and 85 %, respectively (Fig. 3). These thresholds can direct the restoration of these imperiled communities east of the Mississippi river, where work has been scarce, ineffective (Elliott & Vose 2005; Elliott et al. 2012), or focused on more montane pine communities (Jenkins et al. 2011). Closed-canopy forest conditions, which dominate much of the eastern US, had strong, negative influences; however, manipulating those conditions achieved positive results. Under prerequisite conditions (*e.g.*, adequate seed sources and appropriate site histories), fire and canopy disturbance could be effective alternatives to expensive plantings (Anderson et al. 2016). Disturbance long after the cessation of regular burning resulted, at times, in a robust *P. echinata* (>3,000 stems ha^{-1}) and C_4 grass (>40,000 stems ha^{-1}) response. This demonstrates community resiliency after correcting altered disturbance regimes.

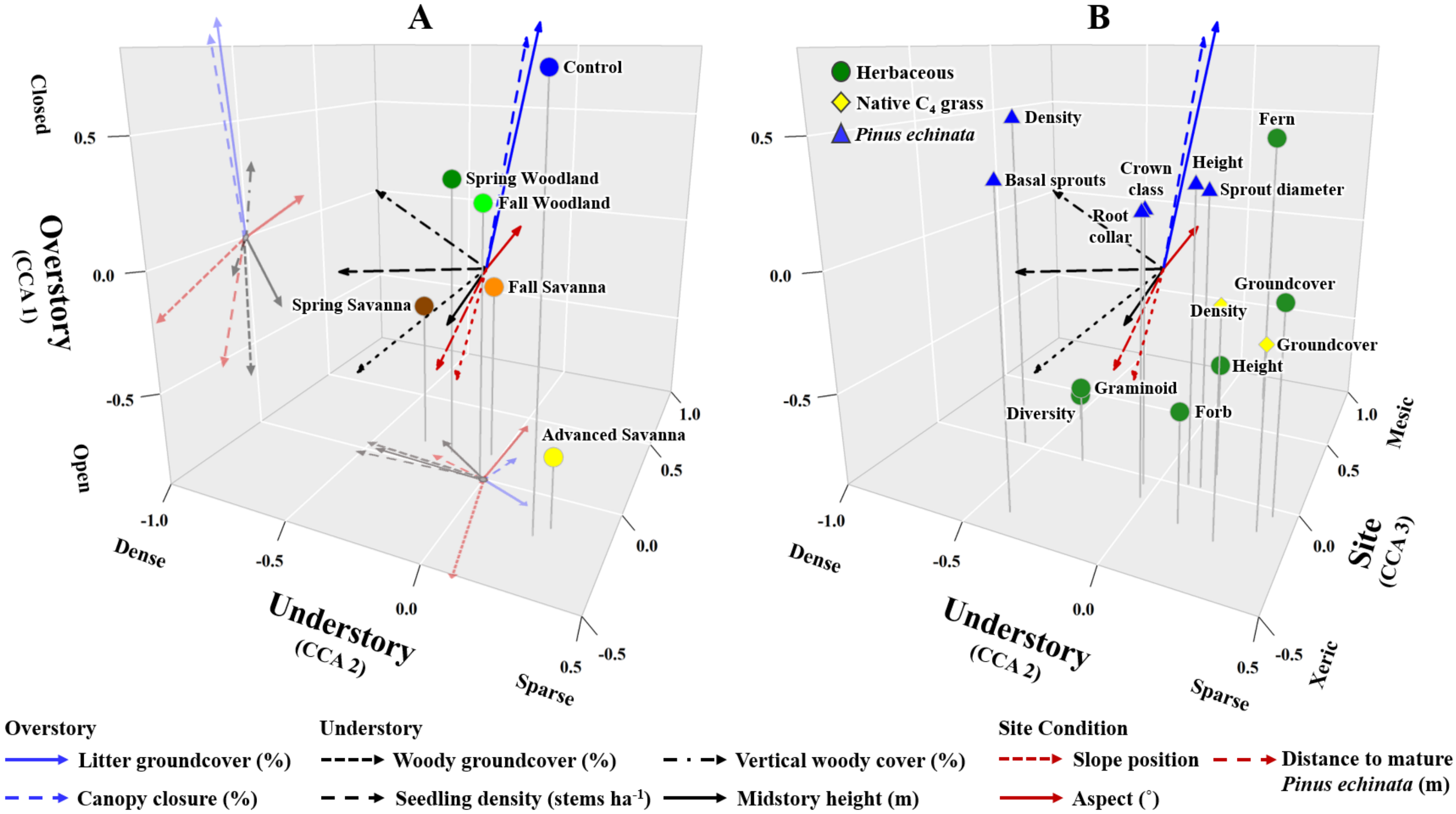

Fig. 2. Shortleaf-bluestem community response along three gradients (CCA, $P \leq 0.016$) describing open to closed canopies, dense to sparse woody understory, and xeric to mesic site conditions on the Cumberland Plateau, TN. A) Centroids of restoration treatments. B) Centroids of shortleaf-bluestem response variables. Arrows depict the explanatory variable correlations and were reflected in A to improve axis interpretation. Treatments include unmanaged stands (Control), spring (Sp) or fall (Fa) fire with woodland (14 m^2 ha^{-1}, W) or savanna (7 m^2 ha^{-1}, S) residual basal area, and advanced savannas (AS).

Where shortleaf-bluestem components were absent (canopy closure > 65 %), residual basal area was ≥16 m^2 ha^{-1}. Jenkins et al. (2011) similarly reported the absence of yellow pine seedlings until overstory density was <15 m^2 ha^{-1}. Naturally regenerating *P. echinata* often involves overstory reductions that meet or exceed this threshold (Baker 1992; Shelton & Cain 2000). Recognizing herbaceous species may be even more shade intolerant (Bowles & McBride 1998; Peterson et al. 2007) has important implications for restoration that aims to promote both. Subsequently, less robust woody understories were associated with a more positive shortleaf-bluestem community response. Jenkins et al. (2011) similarly enhanced *P. echinata* regeneration after reducing understory woody density (-80 %) and shrub cover (-90 %), and reducing woody vegetation with fire promotes and perpetuates herbaceous understories, including C_4 grasses (Sparks et al. 1998). Robust herbaceous response where *P. echinata* vigor was reduced (MRT group 5, Fig. 3) suggests restoration may need to balance herbaceous groundcover promotion with ensuring *P. echinata* survival. Clabo (2014) documented substantial fire-induced mortality of *P. echinata* seedlings (up to 55%), and Stambaugh et al. (2007) suggested recruitment may require an 8 to 15 year respite from fire. Expanded results and discussion can be found in chapter 1 of the included dissertation.

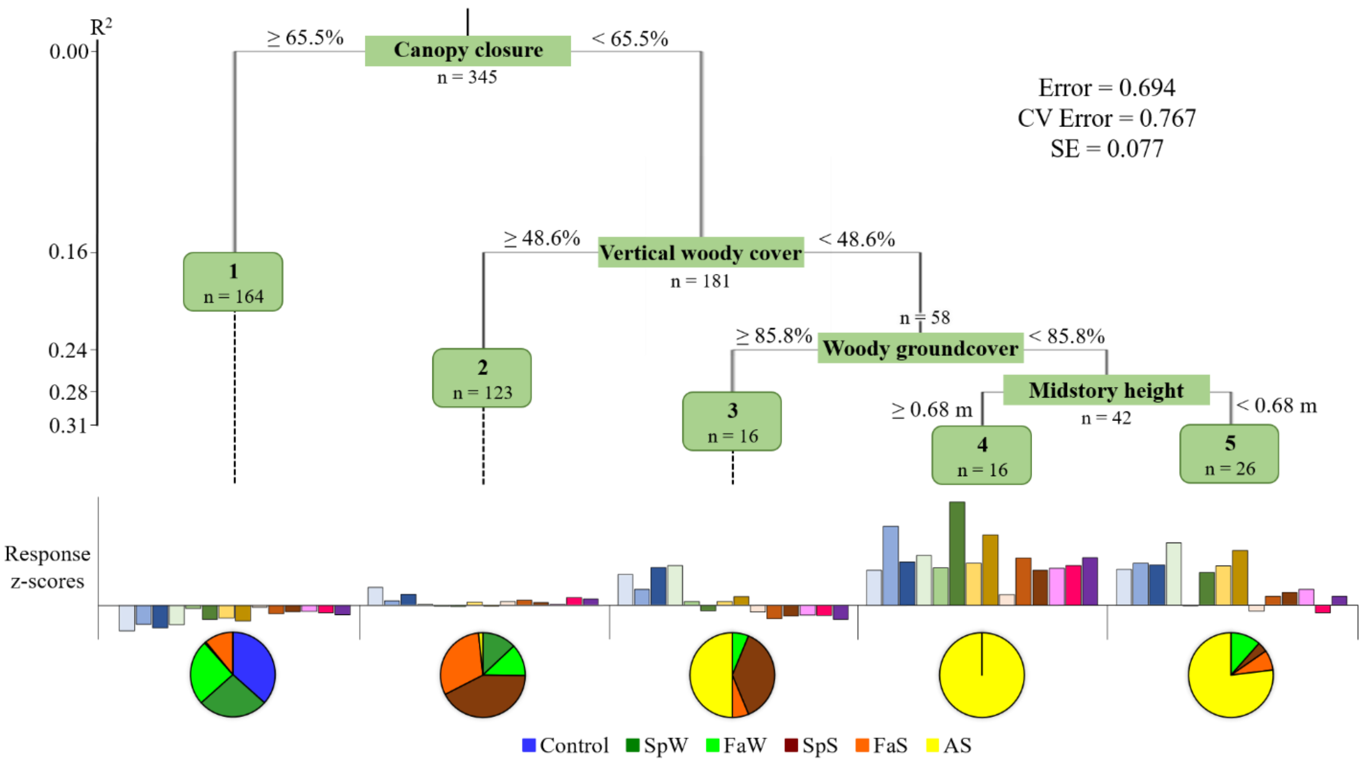

Fig. 3. Multivariate regression tree for shortleaf-bluestem community response to restoration on the Cumberland Plateau, TN. Response z-scores include, from left to right: herbaceous diversity and height; graminoid, forb, fern, and herbaceous groundcover; C_4 grass density and groundcover; density, root collar diameter, height, largest basal sprout diameter, number of basal sprouts, and midstory crown class of *Pinus echinata* regeneration. Selected explanatory variables include; canopy closure (%), vertical woody cover (%), woody groundcover (%), and woody midstory height (m). Tree selected by minimum cross-validated relative error. Treatments include unmanaged stands (Control), spring (Sp) or fall (Fa) fire with woodland (14 m^2 ha^{-1}, W) or savanna (7 m^2 ha^{-1}, S) residual basal area, and advanced savannas (AS).

Fuel-dynamics During Woodland and Savanna Restoration

In agreement with similar regional work (Graham & McCarthy 2006; Waldrop et al. 2016), mechanical thinning and prescribed fire reduced fine-fuels but increased coarse woody fuels (Fig. 4-6). Burn-only, which has limited ecological benefits (Nielsen et al. 2003; Hutchinson et al. 2012), was the only treatment that did not increase in total fuel load. Thinning, regardless of degree, doubled coarse woody fuels by adding nearly 20 Mg ha^{-1}. Burning, even 3 times in 6 years, had little effect on coarse woody fuels. In contrast, treatments reduced leaf litter and 1-h fuels which are key determinants of fire behavior in eastern oak ecosystems (Varner et al. 2015). Fine fuels rebounded from the first to second year following initial fires at all sites, but increases did not match loadings observed prior to burning. Also, biennial fire at CWMA maintained fine-fuel reductions. Herbaceous fuels were sparse (< 1.5 Mg ha^{-1}), and did not compensate for losses in leaf litter; however, increases in herbaceous fuels with thinning and burning suggest this is possible in the future (Fig. 7). Thus, we conclude: (1) thinning and burning reduced fine-fuel loads, but repeated fire is necessary to maintain reductions, and (2) more intensive or prolonged management will be necessary to reduce coarse woody fuel loading. Statistical contrasts supporting results and figures are presented in Appendices E and F.

Mechanical thinning and prescribed fire are effective methods of fuel reduction (Fernandes & Botelho 2003; Andrews & Butler 2006; Stephens et al. 2012), but this evidence is largely derived from work in the western U.S. At one of only two sites characterized by eastern hardwoods within The National Fire and Fire Surrogate study (McIver et al. 2013), Waldrop et al. (2010) concluded the combination of burning and thinning improved short-term (<3 years) resiliency to wildfire by reducing fine-fuels. Our reductions in fine-fuels were comparable, suggesting a similar decline in future wildfire incidence and spread. However, the increases in

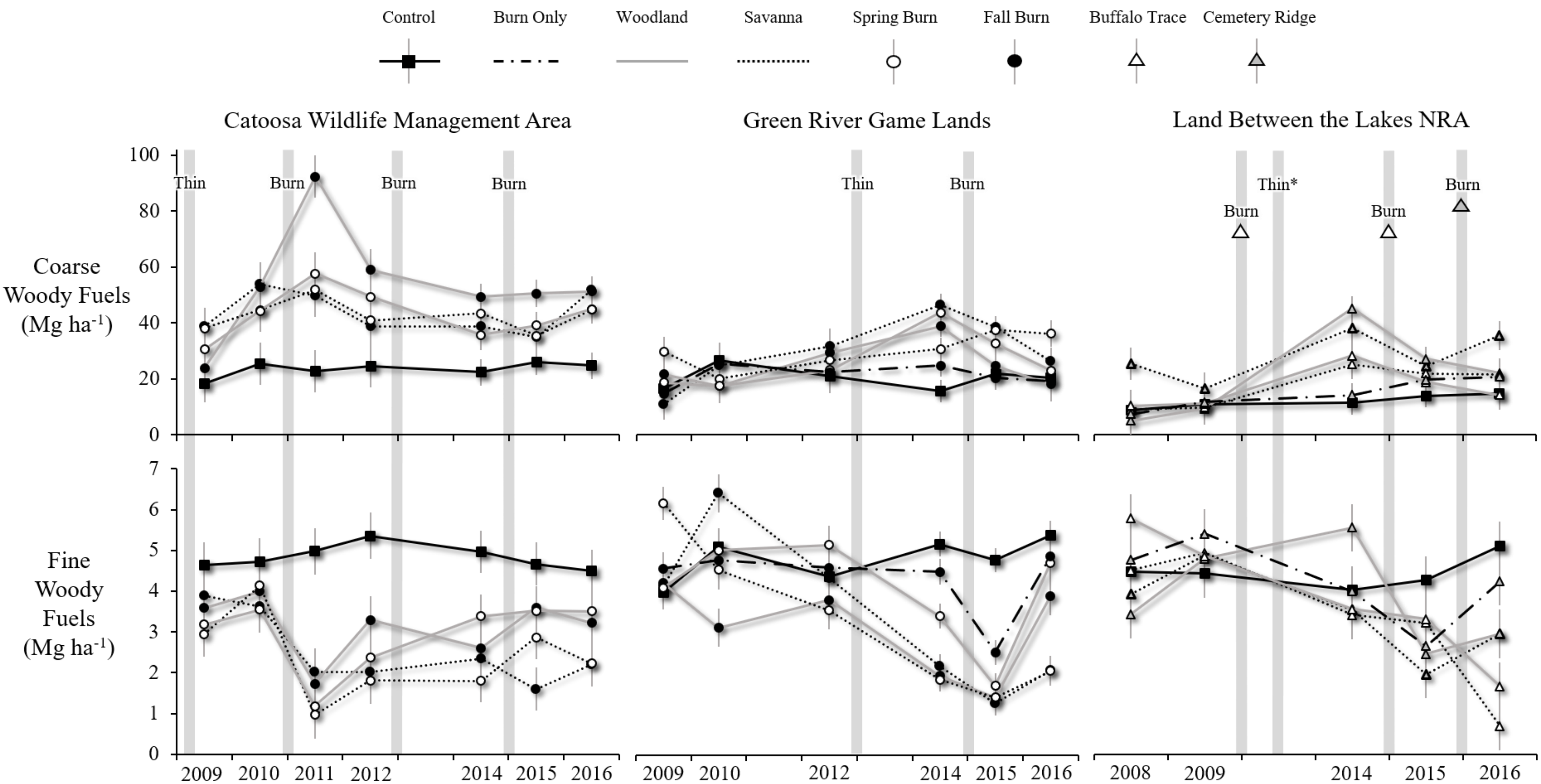

Fig. 4. Observed dynamics in coarse (1000-, 100-, and 10- hour) and fine (1-hour and litter) fuels by oak woodland and savanna restoration treatment during (2008 to 2016) an experiment at 3 sites in the Mid-South. Treatments included unmanaged controls, burn-only in the fall (October) or spring (March), and fall or spring fire paired with woodland (14 m^2 ha^{-1}) or savanna (7 m^2 ha^{-1}) residual basal area. All fires at Land Between the Lakes (LBL) were conducted in the spring, but timing differed between two sites: Buffalo Trace (March) and Cemetery Ridge (April). For LBL and Catoosa, each treatment line represents two 20-ha replicates. Green River had one 20-ha replicate per treatment. *Thinning at LBL occurred over a 3-year period (Fig. 1).

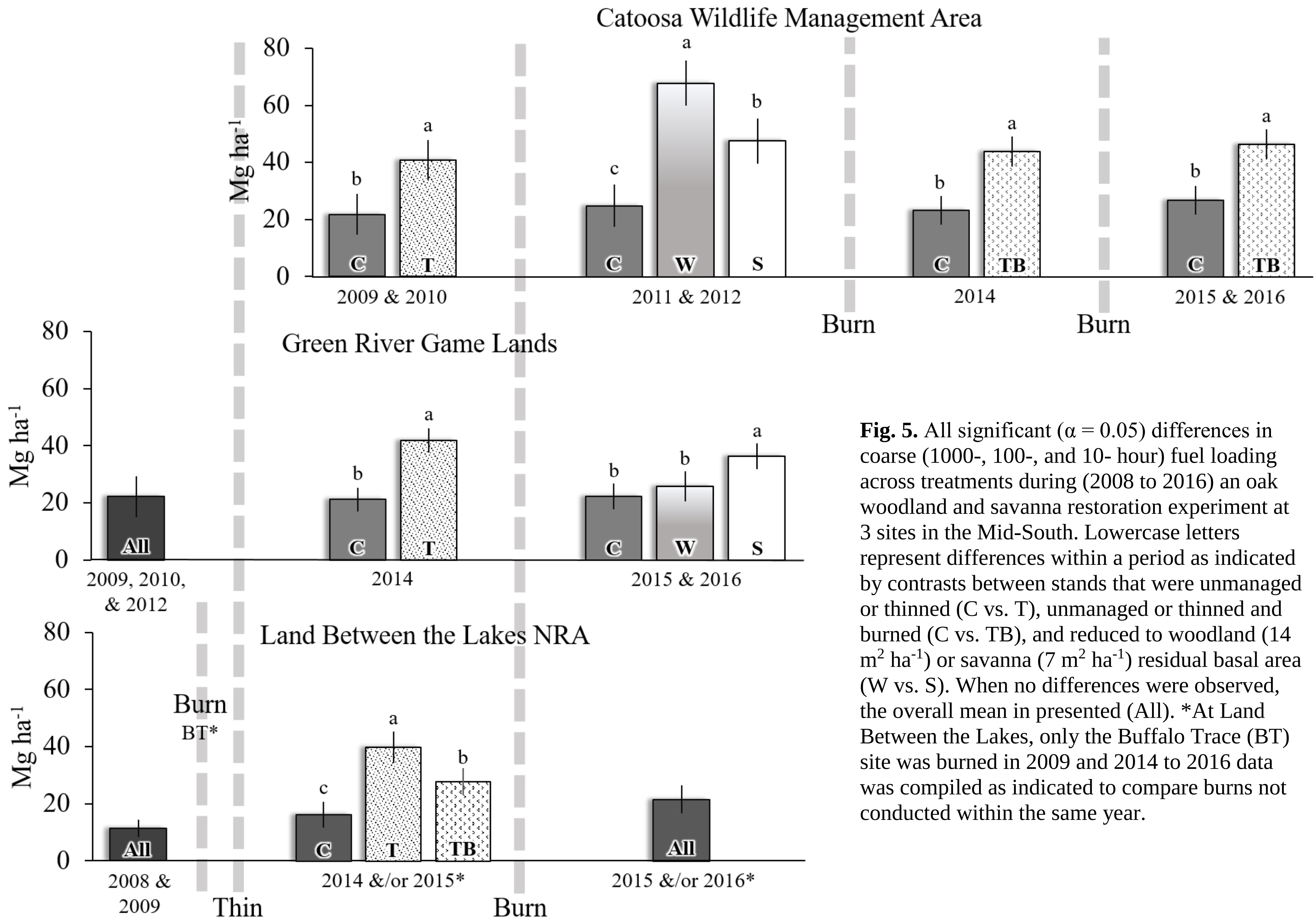

Fig. 5. All significant (α = 0.05) differences in coarse (1000-, 100-, and 10- hour) fuel loading across treatments during (2008 to 2016) an oak woodland and savanna restoration experiment at 3 sites in the Mid-South. Lowercase letters represent differences within a period as indicated by contrasts between stands that were unmanaged or thinned (C vs. T), unmanaged or thinned and burned (C vs. TB), and reduced to woodland (14 $m^2\ ha^{-1}$) or savanna (7 $m^2\ ha^{-1}$) residual basal area (W vs. S). When no differences were observed, the overall mean in presented (All). *At Land Between the Lakes, only the Buffalo Trace (BT) site was burned in 2009 and 2014 to 2016 data was compiled as indicated to compare burns not conducted within the same year.

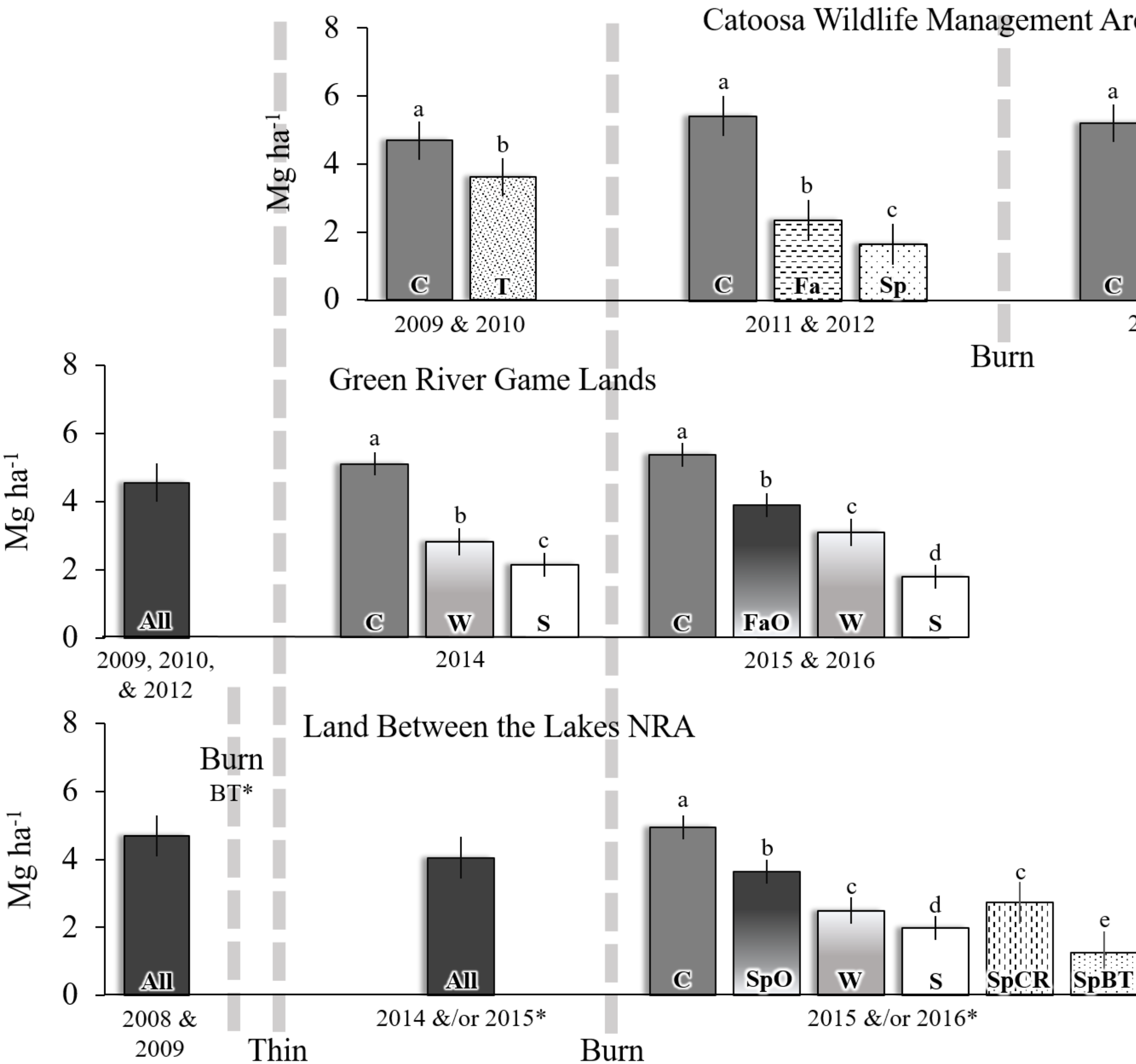

Fig. 6. All differences (α = 0.05) in fine (1- hour and litter) fuel loads across treatments during (2008 to 2016) an oak woodland and savanna restoration experiment at 3 sites in the Mid-South. Lowercase letters represent differences within a period as indicated by contrasts between stands that were unmanaged or thinned (C vs. T), unmanaged or burned only in the fall (C vs. FaO) or spring (C vs. SpO), unmanaged or thinned and burned (C vs. TB), reduced to woodland (14 m^2 ha^{-1}) or savanna (7 m^2 ha^{-1}) residual basal area (W vs. S), burned in the fall or spring (Fa vs. Sp), and burned in separate spring fires (SpBT vs. SpCR). No differences are represented by the overall mean (All). *At Land Between the Lakes, only the Buffalo Trace site was burned in 2009 and 2014 to 2016 data were compiled as indicated to compare burns not conducted within the same year.

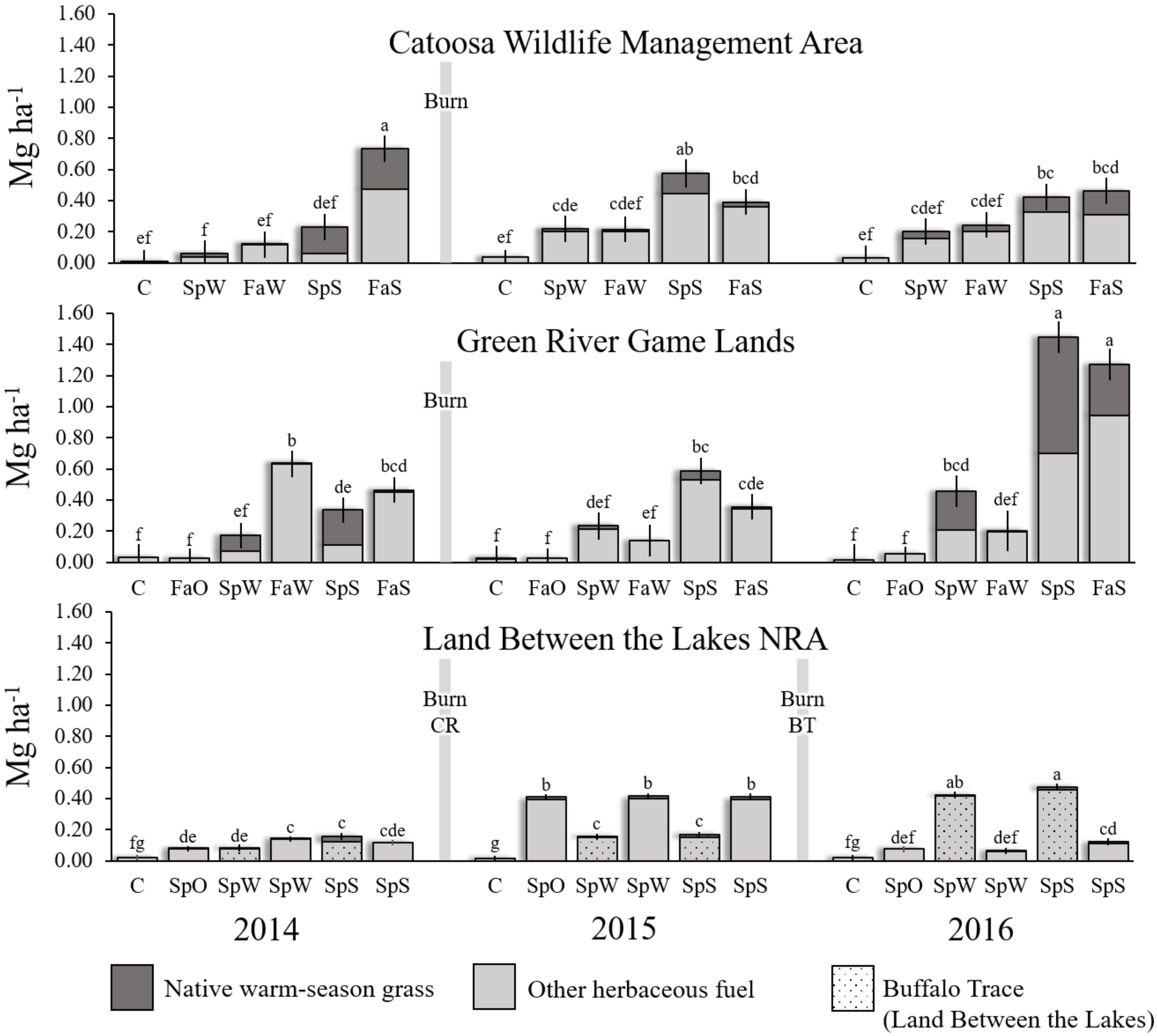

Fig. 7. Herbaceous fuel-loading by treatment and year from 2014 to 2016 of an oak woodland and savanna restoration experiment at 3 sites in the Mid-South. Bars depict fuel composition relative to native warm-season grasses and other herbaceous vegetation. Lowercase letters are differences within a site (2014-2016) by LSD mean separation ($\alpha = 0.05$). Implemented treatments included unmanaged controls (C), burn-only in the fall (FaO) or spring (SpO), and fall or spring fire paired with woodland (FaW or SpW, 14 m^2 ha^{-1}) or savanna (FaS or SpS, 7 m^2 ha^{-1}) residual basal area. All fires at Land Between the Lakes (LBL) were conducted in the spring, but timing differed between two sites: Buffalo Trace (BT) and Cemetery Ridge (CR). For LBL and Catoosa, each treatment bar represents two 20-ha replicates. Green River had one 20-ha replicate per treatment.

coarse woody fuels we documented could greatly increase future wildfire severity if fine-fuel reductions are not maintained with repeated fire. Such maintenance will be increasingly important as air temperatures, drought frequency, and drought duration increase throughout the Mid-South (Mitchell et al. 2014). Proactive management could ease ecological transitions, promote forest health and productivity, preserve ecosystem services, and safeguard communities (Vose & Elliott 2016). Unfortunately, little regionally specific fuel treatment knowledge exists (Waldrop et al. 2016). Our results increase this understanding, but also add urgency. Reducing coarse fuels before climate change effects arrive could require decades of intense management.

Understory Woody Vegetation Response

Management began to reverse the effects of mesophication (Nowacki & Abrams 2008) on the composition and density of understory woody communities at all sites (Fig. 8-10, Appendix G). Thinning and fire increased variation in woody communities (Appendix H) by promoting shade-intolerant and fire-tolerant species. The strong separation between unmanaged and managed stands supports the assertion that a lack of disturbance has greatly altered woody regeneration dynamics in oak forests of the Mid-South (Dey 2014; Keyser et al. 2016). Nearly all shrubby vegetation responded positively to canopy disturbance and fire. Averaged across sites, oak seedling density from pre- to post-management nearly doubled (+2,256 stems ha^{-1} ± 434 SE). Similar trends were observed for other xerophytic and fire-tolerant seedlings. Effects on saplings were less dramatic; however, indicator analysis only associated oaks and other xerophytic saplings with managed treatments (Appendices I1-I3). Species associated with unmanaged stands were generally shade-tolerant, mesophytic species. Paradoxically, red maple was often an exception, and perhaps limited the response of oaks and other xerophytic species in managed stands. Fire-season effects were not observed univariately, but multivariate results

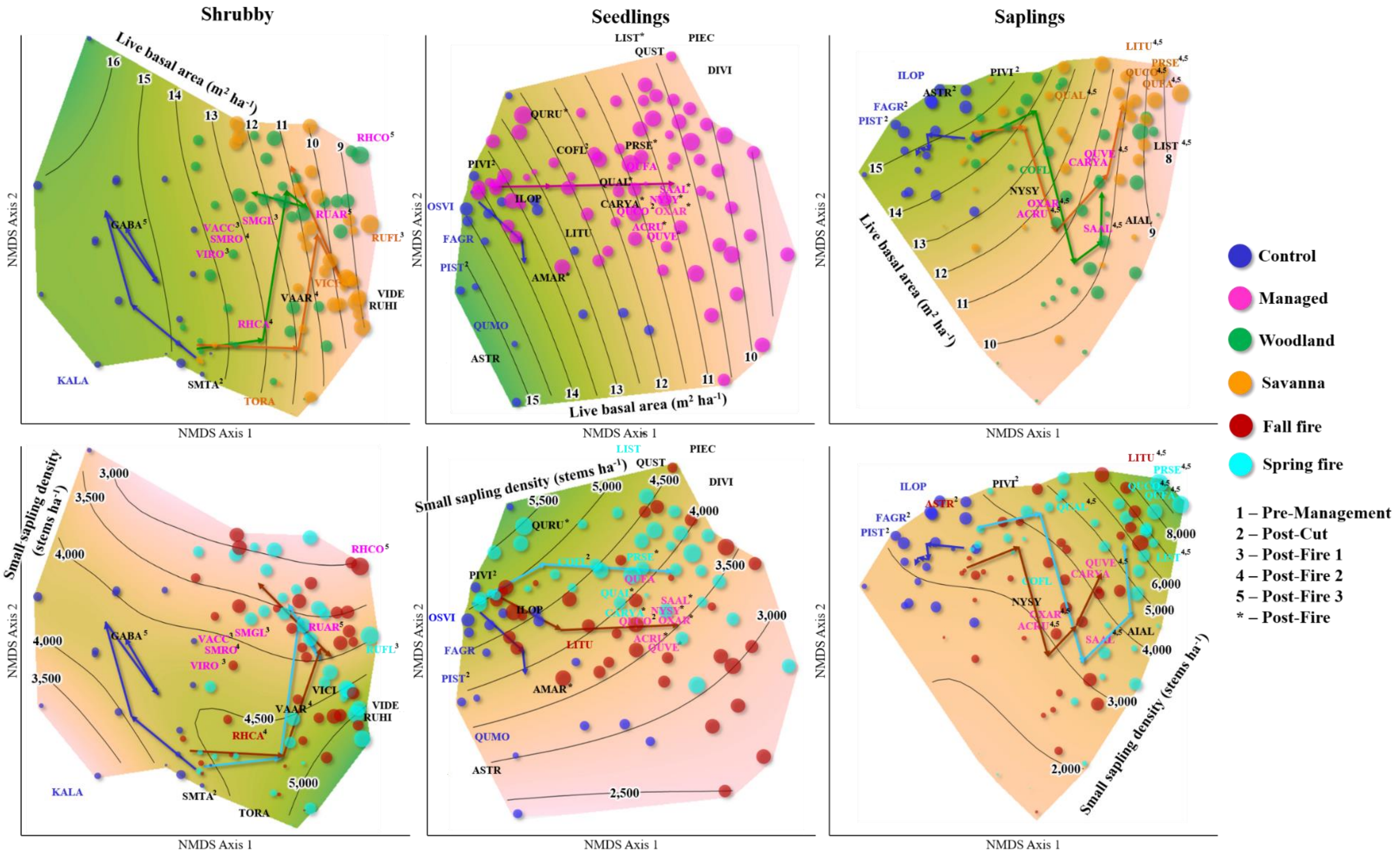

Fig. 8. NMDS ordinations of shrubby, seedling, and sapling density and composition at Catoosa Wildlife Management Area during an oak woodland and savanna restoration experiment involving variation in canopy disturbance (Woodland: 14 m^2 ha^{-1}, Savanna: 7 m^2 ha^{-1}) and prescribed fire-season (Fall, October or Spring, March). Ordinated positions of 20-ha stands (n = 10) within a year (2008 to 2016) are colored based on restricted PERMANOVA (4,999 permutations) determined differences ($\alpha = 0.05$) and size-scaled to density (stems ha^{-1}). Species are colored (treatment) and super-scripted (period) according to indicator analysis results. Arrows depict changes across pre-management to post-fire periods. Rows depict differences in canopy disturbance (top) and fire-season (bottom) treatments. Contour surfaces are predicted live basal area and small sapling density from structured additive regression, and are significantly related to the ordinations they underlie. Ordinated species position is coded to the first two letters of genus and species, and only species that were ≥1% of total density at ≥10% of stands within a year were included.

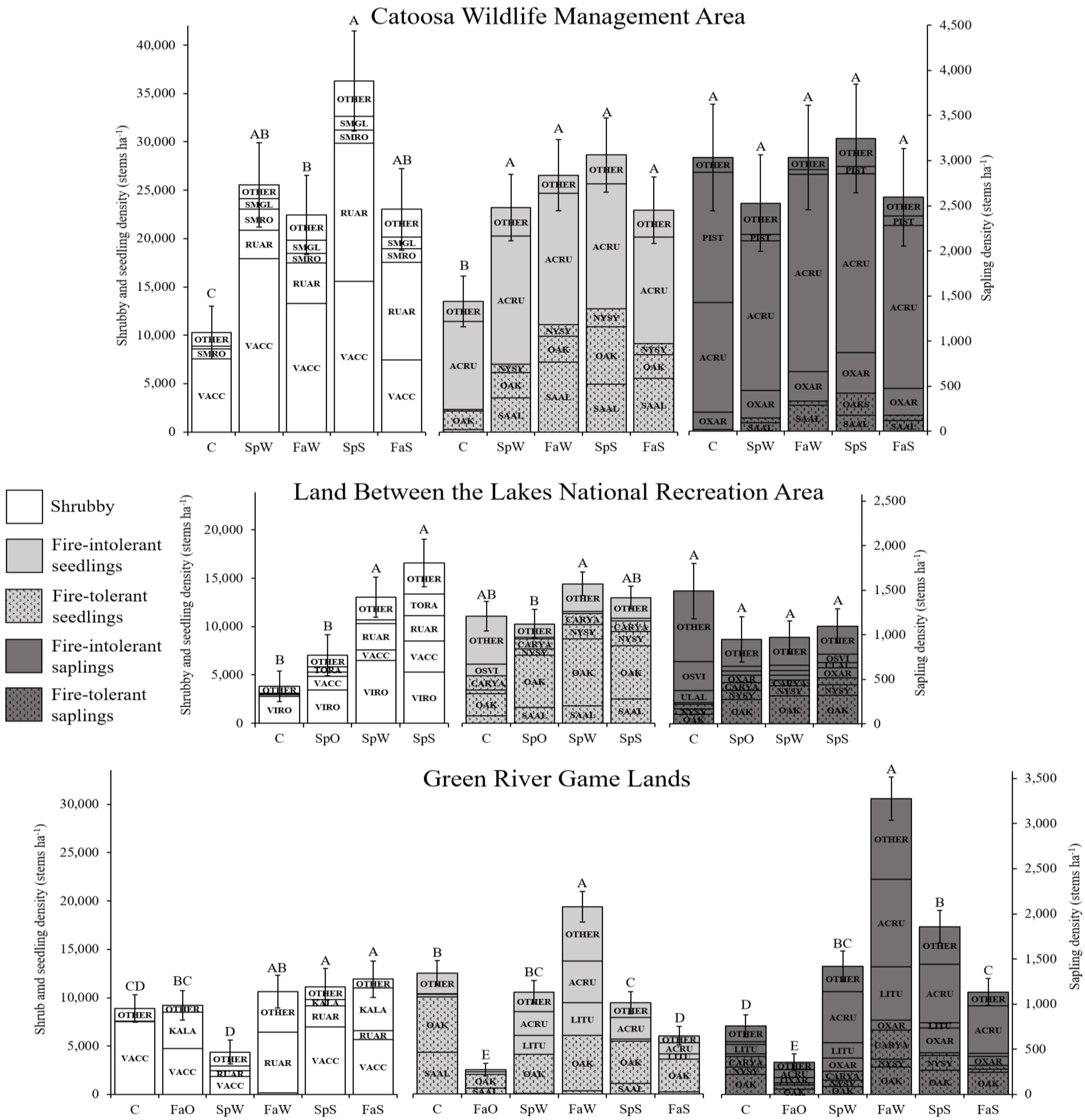

Fig. 9. Differences in shrub, seedling, and sapling communities by treatment at three sites as determined by mixed-effect ANOVA. Treatments were unmanaged (Control), burned only in the spring (SpO) or fall (FaO), and combinations of spring and fall fire with woodland (14 m^2 ha^{-1}) or savanna (7 m^2 ha^{-1}) residual basal area. Individual species accounting for ≥ 5% of the total stem density within any one treatment are presented and coded to the first two letters of genus and species. Shrubby vegetation included multi-stemmed woody and semi-woody (e.g., *Smilax* and *Rubus* spp.) species rarely >4 m tall and lianas. Seedlings are tree species (≥4 m in height at maturity) ≥30.5 cm tall but <1.4 m tall. Saplings are tree species ≥1.4 m tall and <7.6 cm diameter at breast height. All *Carya* spp. (CARYA), Quercus spp. (OAKS), and *Vaccinium* spp. (VACC) except *Vaccinium arboreum* were aggregated.

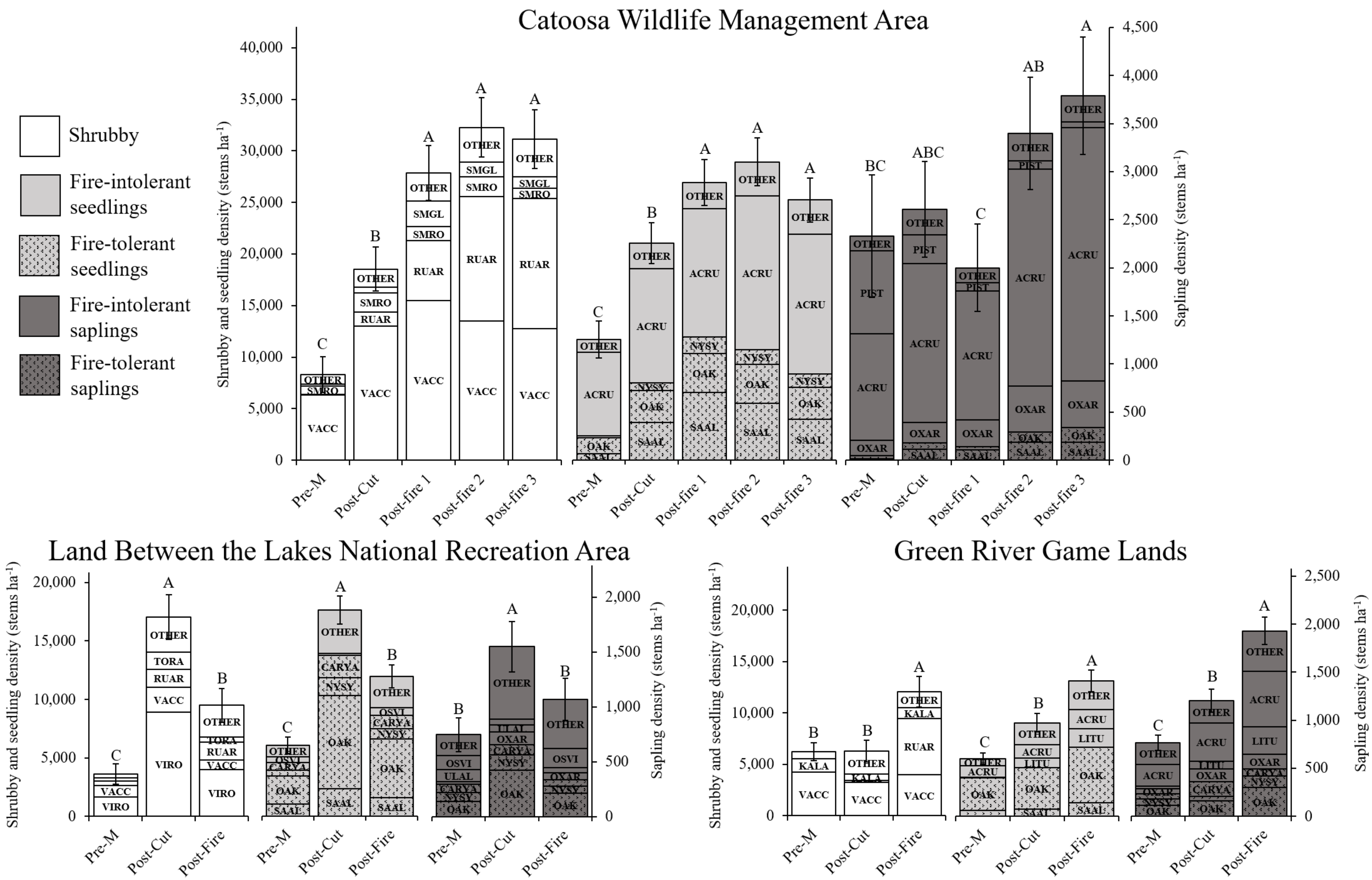

Fig. 10. Differences in shrub, seedling, and sapling communities across periods within the restoration process at three sites as determined by mixed-effect ANOVA. Periods were pre-management (Pre-M), post canopy disturbance (Post-Cut), and post prescribed fire (Post-Fire, multiple at CWMA). Individual species accounting for ≥ 5% of the total stem density within any one treatment are presented and coded to the first two letters of genus and species. Shrubby vegetation included multi-stemmed woody and semi-woody (e.g., *Smilax* and *Rubus* spp.) species rarely >4 m tall and lianas. Seedlings are tree species (≥4 m in height at maturity) ≥30.5 cm tall but <1.4 m tall. Saplings are tree species ≥1.4 m tall and <7.6 cm diameter at breast height. All *Carya* spp. (CARYA), Quercus spp. (OAKS), and *Vaccinium* spp. (VACC) except *Vaccinium arboreum* were aggregated.

suggested spring burning was associated with more woody species and a greater understory density than fall burning. For a full results and discussion relative to woody vegetation response to implemented treatments, please consult Chapter 3 in the included dissertation.

<u>*Herbaceous Ground-layer Response*</u>

Our results demonstrate the utility of canopy disturbance and fire for restoring herbaceous ground-layers in oak forests throughout the Mid-South. Like in the Midwest (Nielsen et al. 2003; Brudvig & Asbjornsen 2009; Lettow et al. 2014), both canopy disturbance and fire contributed to promoting herbaceous groundcover and diversity. We encountered 46 unique herbaceous species prior to management across all sites. By 2016, the conclusion of monitoring, we cumulatively documented 370 herbaceous species (Dissertation Chapter 4). Similar site-specific figures indicated 12.7-fold (CWMA, 21 to 266 species), 7.3-fold (GRGL, 28 to 203 species), and 5.1-fold (LBL, 43 to 218 species) increases in herbaceous richness. Herbaceous diversity was greater in treatments than controls at all sites by the conclusion of monitoring, and herbaceous groundcover increased >4-fold in some treatments (Appendix J, Fig. 11-12). This provides regionally specific evidence of the elsewhere well-established link between fire and open-oak community restoration (Peterson et al. 2007).

Graminoid response was dominated by the genera *Dichanthelium*, *Carex*, *Piptochaetium*, *Chasmanthium*, and *Danthonia*. Broomsedge (*Andropogon virginicus* L.) was also common. We observed significant treatment × year interactions for graminoid groundcover at all sites. This generally involved greater increases in treatments relative to controls, and greater increases in savannas relative to woodlands (Appendix J, Fig. 11). American burnweed (*Erechtites hieraciifolia* [L.] Raf. ex DC.) was the most, or second most, commonly encountered forb at all three sites. Across sites, *Eupatorium* (9 species), *Solidago* (15 species), and *Viola* (10 species) genera accounted for substantial portions of forb diversity. Many frequently encountered species were shared between CWMA and GRGL, but herbaceous composition at LBL was more distinct; six of the top ten most frequently encountered forbs at LBL were legumes. The genera *Lespedeza* (7 species) and *Desmodium* (9 species) were common across all sites. Forb groundcover also increased more in treatments relative to controls (Appendix J, Fig. 11). Please consult Dissertation Chapter 4 for a full account of herbaceous-layer response to treatments.

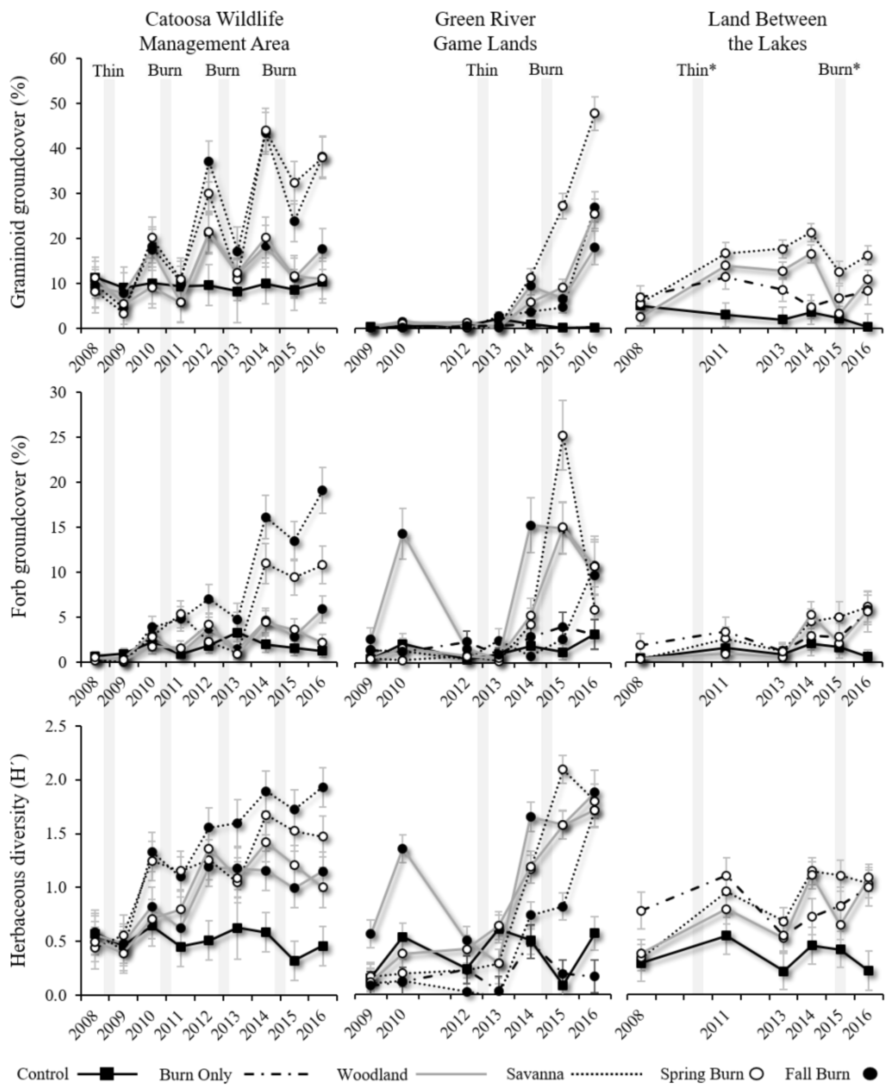

Fig. 11. Graminoid and forb groundcover, and herbaceous diversity (Shannon-Wiener Index), during (2008 to 2016) oak woodland and savanna restoration experiments at 3 sites located across the Mid-South. Treatments included unmanaged oak forests (Control), burn only in spring or fall, and savanna (7 m^2 ha^{-1}, S) or woodland (14 m^2 ha^{-1}, W) residual basal area paired with spring or fall fire.

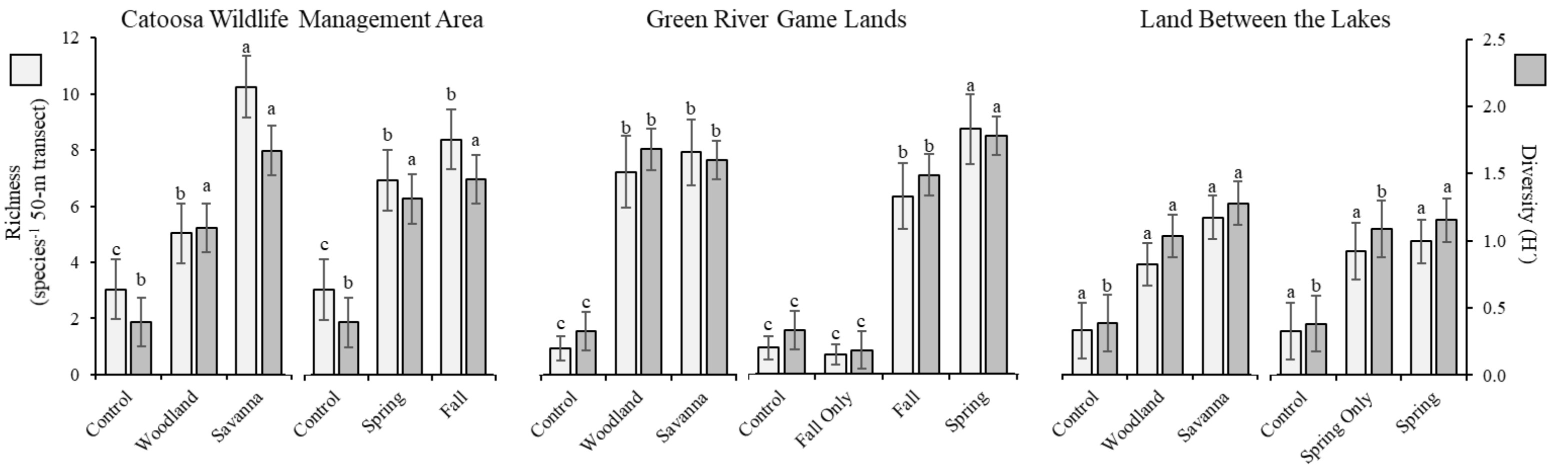

Fig. 12. Differences in herbaceous richness and diversity (Shannon-Wiener Index) in the final two years of monitoring (2015 and 2016) oak woodland and savanna restoration experiments at 3 sites located across the Mid-South. Treatments included unmanaged oak forests (Control), burn only in spring or fall, and savanna (7 m^2 ha^{-1}, S) or woodland (14 m^2 ha^{-1}, W) residual basal area paired with spring or fall fire. Lowercase letters represent significant ($\alpha = 0.05$) differences by orthogonal contrast tests.

Science Delivery Activities

All proposed deliverables were completed or are in progress (Appendix B). In the future, we intend to relate documented fuel-load dynamics to potential changes in fire behavior. A time series analysis will characterize post-fire litter reaccumulation rates of fuel loading in restoration treatments, and describe changes in the accumulation of individual time-lag fuel classes. Initial work included changes in fuels at Catoosa Wildlife Management Area as predicted by the Forest Vegetation Simulator (FVS); a commonly used software tool for estimating and predicting changes due to forest management activities. Fire behavior due to changing fuel loading was simulated by inputting stand conditions, environmental conditions, and fuel loadings to FVS. FVS also allowed us to project forward the likely changes in forest compositions, structure, and fire behavior expected from long-term implementation of restoration treatments. In the future, we intend to complete the analysis of temporal changes in fuel loading and type including the effects on modeled fire behavior.

Implications for Management, Policy, and Future Research

Shortleaf-Bluestem Community Restoration

A cascade of canopy closure, understory thickness, and site-condition effects were associated with the response of keystone shortleaf-bluestem community components. Promoting *P. echinata* and C_4 grasses begins with reducing the overstory below 65 % closure or 16 m^2 ha^{-1} basal area. Repeated fire can then target threshold understory conditions, including vertical woody cover in the understory (< 48 %) and woody groundcover (< 85 %). Intense fire can create these conditions; however, moderating intensity with strip-head firing could retain more *P. echinata* than the intense ring-firing used at CWMA. Late growing-season fire may harm *P. echinata* vigor, but this should be weighed against the potential for increased competition control and herbaceous development. Restoration should be most effective along ridges, southwest aspects, and downwind from mature *P. echinata*. Unmanaged forests (controls) had minimal, if any, shortleaf-bluestem community response. Canopy disturbance and fire simultaneously promoted *P. echinata* and C_4 grass, reflecting their historically intimate association. While this demonstrates resiliency, it also suggests that without active management shortleaf-bluestem communities could soon vanish from the eastern US.

Effectiveness of Restoration Associated Fuel-Treatments

Past fire suppression and future climate change threaten to disrupt historical fuel-dynamics in the Mid-South. Oak woodland and savanna restoration require thinning and prescribed fire, and these techniques can reduce fuels and wildfire risk. However, our results clearly demonstrate that returning disturbance after a prolonged absence can increase total fuel loading. Thinning added 20 Mg ha^{-1} of logging slash that remained even after 3 fires in 6 years. Fine-fuels were reduced, but maintaining reductions will require continued burning every 2 to 3 years. Even then, increases in herbaceous fuels could potentially compensate for the loss of leaf litter and twigs within 10 years under open (7 m^2 ha^{-1}) canopies. Where fuel reduction is a priority, applied techniques could be more specifically designed to remove fuels. This could include the complete removal of logging debris or mulching into smaller pieces that would be more readily consumed by prescribed fire. Greater canopy cover could be retained to preclude increases in herbaceous fuels, but this will limit restoration progress. All fire-sensitive tree species should be removed from the overstory to prevent future fuel inputs as snags deteriorate. Moderately intense fire, capable of consuming fuel while limiting overstory mortality, could make a critical contribution to a long-term reduction in loading of heavier fuels. Our results suggest restoration-associated thinning increases coarse fuel-loads, and reducing such loads with prescribed fire could take decades. Future research is needed to evaluate whether long-term management that shifts fine-fuel composition, and not necessarily amounts, from litter and twigs to herbaceous plants represents a decrease in wildfire severity or risk.

Reversing Mesophication Effects on Understory Woody Vegetation

At sites located across the Mid-South, we used disturbance to increase the density of shade-intolerant and fire-tolerant species that were suppressed prior to management. Shifts in shrubby, seedling, and sapling layers were directly related to the effects of canopy disturbance on overstory density, and the effects of fire on understory density. Managing for historical savanna conditions (7 m^2 ha^{-1}) increased the understory density of oaks and other xerophytic species, and did not promote shade-intolerant competitors (*e.g.*, yellow poplar) more so than woodland conditions (14 m^2 ha^{-1}). Thus, heavy canopy disturbance may be an under-utilized tool for reversing mesophication effects in the eastern U.S. We also demonstrated the greater effectiveness of management in altering woody communities on xeric sites where mesophytic competitors are less abundant. We did not find strong evidence of differences between October and March fires, but further research comparing alternative fire-seasons is warranted. After disturbance adequately promotes oaks and other fire-tolerant species in the understory, gaps in fire recurrence could be required to recruit such regeneration into the overstory. Priming the woody regeneration pool of eastern oak ecosystems now with active management could prepare managers for action when such strategies are indicated, and increase the resiliency of regional forests to forecasted climatic and environmental changes.

Establishing Robust and Diverse Herbaceous Groundcover

Our work adds substantially to limited knowledge concerning the promotion of herbaceous ground-layers in oak communities of the Mid-South region. The greater than 4-fold increases in herbaceous groundcover and diversity that we observed following thinning and prescribed fire demonstrate the resiliency of this component of oak woodlands and savannas. Canopy disturbance to a basal area of 7 m^2 ha^{-1} resulted in progress toward oak savanna restoration, while 15 m^2 ha^{-1} resulted in more limited woodland restoration progress. Both canopy disturbance and fire were important for promoting increases in herbaceous cover, richness, and diversity. Repeated burning will be required to maintain, and further promote, the increases in herbaceous groundcover and reductions in woody competition. Because resprouting often returned small-sapling density to pre-fire levels by the second growing-season following fire, we recommend an initial 2-year fire return interval. This will maximize woody control while allowing fine-fuel loads to recharge. We documented a similar herbaceous response to October and March fires even though October fires were less intense. Combining the safety implication of fall burning with research that suggests late growing-season fire is more effective in controlling hardwoods should cause managers to explore burning outside of the traditional dormant-season. Our results were generally consistent across landscape variation and herbaceous diversity benefitted from including drains and swales within management sites. Long-term research documenting the response of vegetation to successively applied fires is needed to advance oak woodland and savanna restoration throughout the Mid-South region.

Appendices

Appendix A. Contact Information for Key Project Personnel

Personnel	Role	Contact Information	Email
Patrick D. Keyser	Principal Investigator	University of Tennessee-Knoxville, Dept. of Forestry, Wildlife, & Fisheries, 274 Ellington Plant Sciences, Knoxville, TN, 37996 USA	pkeyser@utk.edu
Charles Kwit	Co-principal Investigator	University of Tennessee-Knoxville, Dept. of Forestry, Wildlife, & Fisheries, 274 Ellington Plant Sciences, Knoxville, TN, 37996 USA	ckwit@utk.edu
Michael C. Stambaugh	Co-principal Investigator	University of Missouri, Dept. of Forestry, 203C Anheuser-Busch Natural Resources Building, Columbia, MO 65211 USA	stambaughm@missouri.edu
Andrew L. Vander Yacht	Co-principal Investigator	Michigan State University, Dept. of Forestry, 106 Natural Resources Building, East Lansing, MI, 48824 USA	vandery1@msu.edu

Appendix B. Deliverables

Dates	Deliverable	Description
4/20/2018	Ph.D. Dissertation	Dissertation entitled "*Vegetation and Fuel Dynamics During Woodland and Savanna Restoration in the Mid-South USA"* submitted and published in the Tennessee Research and Creative Exchange (TRACE), the University of Tennessee's open repository.
3/20/2018	Refereed Publication 1	Manuscript entitled "*Pinus echinata and Warm-season Grasses: Patterns in Establishing Keystone Components Informs the Restoration of an Imperiled Fire-Dependent Community*" submitted to Applied Vegetation Science (Dissertation Chapter 1).
4/20/2018	Refereed Publication 2	Manuscript entitled "*Fuel Load Dynamics During Woodland and Savanna Restoration in the Mid-South*" submitted to International Journal of Wildland Fire (Dissertation Chapter 2).
5/20/2018	Refereed Publication 3	Manuscript entitled "*Using Thinning and Fire to Reverse Mesophication Effects on Woody Vegetation in Oak Forests of the Mid-South*" submitted to Forest Science (Dissertation Chapter 3).
6/20/2018	Refereed Publication 4	Manuscript entitled "*Promoting Herbaceous Groundcover and Diversity with Canopy Disturbance and Fire in Central Hardwood and Appalachian Oak Forests*" submitted to Fire Ecology (Dissertation Chapter 4).

9/20/2018	Refereed Publication 5	Manuscript entitled “Oak Woodland and Savanna Restoration: Implications of Altered Fuel Dynamics on Fire Behavior” submitted to Unknown Journal (Dr. Mike Stambaugh Contribution).
6/15/2016	Non-refereed publication 1	University of Tennessee Institute of Agriculture Extension Publication PB 1812, “*Ecology and Management of Oak Woodlands and Savannahs*”, https://extension.tennessee.edu/publications/Documents/PB1812.pdf
7/20/2018	Non-refereed publication 2	Will work with Oak Woodlands and Forests Fire Consortium to publish a manager focused technical bulletin on fuels and fuel treatments in eastern oak forests.
10/21-24/2014	Conference/symposia 1	Vander Yacht, A.L., Keyser, P.D., Buehler, D.A., Barrioz, S.A. 2014. Avian Occupancy Response to Oak Savanna and Woodland Restoration in Tennessee. Our Roots Run Deep: 10th Biennial Longleaf Conference and 9th Eastern Native Grass Symposium. Mobile, AL, Oct. 22.
10/25-30/2014	Conference/symposia 2	Vander Yacht, A.L., Keyser P.D., Buehler, D.A., Harper, C.A., Buckley, D.S., and Applegate, R.D. 2014. Avian Occupancy Response to Oak Savanna and Woodland Restoration in Tennessee. 21st Annual Conference of The Wildlife Society, Pittsburgh, PA, Oct. 26.
5/27-29/2015	Conference/symposia 3	Vander Yacht, A.L., Keyser P.D., and Kwit, C. 2015. Poster: Converting Oak Forests to Oak Grasslands: Thresholds in Herbaceous Response to Canopy Disturbance on the Cumberland Plateau, TN. 5th Fire in Eastern Oak Forests Conference, Tuscaloosa, AL, May 27-29.
11/1-4/2015	Conference/symposia 4	Cox, M. R., Willcox, E.V., Keyser, P.D., and Vander Yacht, A.L. 2015. Prescribed Fire and Overstory Thinning Increase Bat Activity in Tennessee Hardwood Forests. 69th Annual Conference of the Southeastern Association of Fish and Wildlife Agencies, Asheville, NC, Nov. 1-4.
5/25-27/2016	Conference/symposia 5	Vander Yacht, A.L., Keyser P.D., Willcox, E., Henderson, C., and Cox, M. 2016. Field of Dreams: Vegetation and Wildlife Response to Oak Woodland and Savanna Restoration in Tennessee. The Mid-South Prairie Symposium, Clarksville, TN, May 25-27.
10/24-26/2017	Conference/symposia 6	Keyser, P.D., Vander Yacht, A.L., Henderson, C.A., Willcox, E.V., Cox, M.R., Buehler, D.A., Harper, C.A., Kwit, C.X., Stambaugh, M.C. 2017. Wildlife Response to Oak Ecosystem Restoration. Oak Symposium 2017: Sustaining Oak Forests in the 21st Century through Science-based Management. Knoxville, TN, Oct. 24-26.
9/29/2017	Conference/symposia 7	Vander Yacht, A.L. 2017. Islands in a Forested Sea: The Conservation Value of Oak Woodlands and Savannas Demonstrated on Tennessee’s Cumberland Plateau. Oak Woodlands and Fire Consortium Workshop: Fire and Forest Management in Middle Tennessee, Tullahoma, TN, Sept. 29.
9/23/2015	Field tour, CWMA	Clatterbuck, W. K., Coffey, C., Bowers, J., and Vander Yacht, A.L. 2015. Shortleaf Pine Research and Management at Catoosa Wildlife

		Management Area. 3rd Biennial Shortleaf Pine Conference, Knoxville, TN.
12/13/2017	Workshop, GRGL	Keyser, P., A. Vander Yacht, C. Henderson, E. Willcox, M. Cox, D. Buehler, C. Harper, C. Kwit, and M. Stambaugh. 2017. Cooperative Oak Ecosystem Restoration Project. Marion, NC.
10/6/2015	Field tour, LBL	Vander Yacht, A.L., Henderson, C., and Wilson, D. 2015. Oak Woodland and Savanna Restoration at Land Between the Lakes National Recreation Area. 7th Annual Meeting of the Kentucky Prescribed Fire Council, Hardin, KY.
7/22/2015	Field tour, LBL	Keyser, P.D. and Vander Yacht, A.L. Land Between the Lakes NRA Advisory Board Tour of Oak Grassland Demonstration Sites, Golden Pond, KY.
6/2/2014	Field tour, LBL	Keyser, P.D., and Vander Yacht, A.L. 2014. Oak Woodland Restoration at Land Between the Lakes NRA: Avian, Herbaceous, and Woody Regeneration Response. Prescribed Fire in the Mid-South Conference, Crossville, TN.
March 2014	In-Service Training Session 1	National Advanced Silviculture Program, Lecture and Field Tour of Oak Woodland and Savanna Management at Catoosa Wildlife Management Area, Knoxville and Crossville, TN
March 2015	In-Service Training Session 2	National Advanced Silviculture Program, Lecture and Field Tour of Oak Woodland and Savanna Management at Catoosa Wildlife Management Area, Knoxville and Crossville, TN
March 2016	In-Service Training Session 3	National Advanced Silviculture Program, Lecture and Field Tour of Oak Woodland and Savanna Management at Catoosa Wildlife Management Area, Knoxville and Crossville, TN
March 2017	In-Service Training Session 4	National Advanced Silviculture Program, Lecture and Field Tour of Oak Woodland and Savanna Management at Catoosa Wildlife Management Area, Knoxville and Crossville, TN
5/20/2018	Datasets	All fuel and vegetation datasets archived in the US Forest Service Research Data Archive

Appendix C. Metadata

Data collected for this project includes vegetation and fuels data, fire simulation data, and invertebrate richness and biomass data. All data is stored as .csv and can be accessed from the US Forest Service Research Data Archive.

Appendix D. Seasonal comparison of weather, fuel moisture, and fire behavior for prescribed fires during an oak woodland and savanna restoration experiment at Catoosa Wildlife Management Area (CWMA), Green River Game Lands (GRGL), and Land Between the Lakes (LBL). Statistics based on a two-sample t-test assuming unequal variance.

		Fire season				
Variable	Units	Fall	Spring	*t*	*df*	*p*
Ambient temperature	˚C	24.6 ± 0.5	17.6 ± 0.6	8.80	101	< **0.001**
Relative humidity	%	39.0 ± 1.2	38.6 ± 1.5	0.17	110	0.867
Wind speed	$m\ s^{-1}$	1.6 ± 0.2	3.5 ± 0.2	6.86	102	< **0.001**
Wind direction	˚	214.8 ± 15.8	204.5 ± 14.4	0.48	94	0.631
Fine-fuel moisture	%	12.5 ± 0.8	17.0 ± 1.5	2.67	90	**0.009**
10-hour fuel moisture	%	9.2 ± 0.9	10.1 ± 0.6	0.78	22	0.446
Flanking fire rate-of-spread	$m\ min^{-1}$	0.6 ± 0.1	1.1 ± 0.3	1.45	25	0.159
Flanking fire flame-length	m	0.4 ± 0.1	0.6 ± 0.1	1.55	44	0.127
Heading fire rate-of-spread	$m\ min^{-1}$	1.6 ± 0.1	2.9 ± 0.4	3.03	30	**0.005**
Heading fire flame-length	m	0.7 ± 0.1	1.3 ± 0.1	3.61	37	< **0.001**
Fire temperature	˚C	170.6 ± 7.7	210.2 ± 15.3	2.32	122	**0.022**

[1]Fall burns at CWMA: 11 Oct 2010, 24 Oct 2012, and 24 Oct 2014. Spring burns at CWMA: 22 Mar 2011, 15 Mar 2013, and 18 Mar 2015. Fall burn at GRGL: 27 Oct 2014. Spring burn at GRGL: 18 March 2015. Buffalo Trace spring burn at LBL: 29 Mar 2016. Cemetery Ridge spring burn at LBL: 22 Apr 2015.

Appendix E. All differences (α = 0.05) in coarse (1000-, 100-, and 10- hour), fine (1-hour and litter), and herbaceous fuel-loads before and after thinning, and before and after subsequent burning, during (2008 to 2016) an oak woodland and savanna restoration experiment at 3 sites in the Mid-South. Treatment contrasts compared stands that were: unmanaged or thinned (C vs. T), unmanaged or only burned in the fall (C vs. FaO) or spring (C vs. SpO), unmanaged or thinned and burned (C vs. TB), reduced to woodland (14 m^2 ha^{-1}) or savanna (7 m^2 ha^{-1}) residual basal area (W vs. S), burned in the fall or spring (Fa vs. Sp), and burned in separate spring fires (SpBT vs. SpCR). Except for C vs. T, which was always tested, contrast evaluation followed the implementation of involved management.

Site	Fuel category	Period	Year(s)[1]	Contrast	*F*	*p*	Estimate[1] Mg ha^{-1} (SE)
Catoosa WMA	Coarse	Post-thin	2009 & 2010	C vs. T	12.0	0.006	+19.0 (6.0)
		Post-burn 1	2011 & 2012	C vs. TB	16.6	0.002	+31.3 (8.1)
				W vs. S	5.6	0.040	-19.3 (7.2)
		Post-burn 2	2014	C vs. TB	13.1	0.015	+19.4 (5.3)
		Post-burn 3	2015 & 2016	C vs. TB	30.1	< 0.001	+18.7 (3.3)
	Fine	Post-thin	2009 & 2010	C vs. T	15.3	0.003	-1.1 (0.3)
		Post-burn 1	2011 & 2012	C vs. TB	95.3	< 0.001	-3.3 (0.3)
				Fa vs. Sp	7.7	0.020	-0.7 (0.3)
		Post-burn 2	2014	C vs. TB	9.6	0.027	-2.4 (0.8)
		Post-burn 3	2015 & 2016	C vs. TB	10.0	0.010	-1.7 (0.5)
				W vs. S	7.2	0.023	-1.2 (0.5)
	Herbaceous*	Post-burn 2	2014	C vs. TB	10.8	0.022	+0.3 (0.2)
				W vs. S	14.1	0.013	+0.4 (0.1)
		Post-burn 3	2015 & 2016	C vs. TB	46.9	< 0.001	+0.3 (0.1)
				W vs. S	19.7	0.001	+0.2 (0.1)
Green River Game Lands	Coarse	Post-thin	2014	C vs. T	35.9	< 0.001	+19.7 (3.8)
		Post-burn	2015 & 2016	W vs. S	10.2	0.002	+10.1 (3.1)
	Fine	Post-thin	2014	C vs. T	99.2	< 0.001	-2.5 (0.2)
				W vs. S	6.0	0.016	-0.7 (0.3)
		Post-burn	2015 & 2016	C vs. FaO	15.0	< 0.001	-1.4 (0.3)
				C vs. TB	94.3	< 0.001	-2.5 (0.3)
				W vs. S	31.8	< 0.001	-1.2 (0.2)
	Herbaceous*	Post-thin	2014	C vs. T	35.0	< 0.001	+0.4 (0.1)
		Post-burn	2015 & 2016	C vs. TB	171.6	< 0.001	+0.5 (0.1)
				W vs. S	94.9	< 0.001	+0.7 (0.1)
				Fa vs. Sp	18.2	< 0.001	+0.2 (0.1)
Land Between the Lakes	Coarse	Post-thin	2014 &/or 2015*	C vs. T	27.5	< 0.001	+20.2 (4.1)
				C vs. TB	7.6	0.017	+8.7 (3.8)
	Fine	Post-burn	2015 &/or 2016*	C vs. SpO	34.7	0.001	-1.3 (0.2)
				C vs. TB	307.5	< 0.001	-2.8 (0.2)
				W vs. S	30.4	0.002	-0.6 (0.2)
				SpBT vs. SpCR	106.3	< 0.001	+1.4 (0.2)
	Herbaceous*	Post-thin	2014 &/or 2015*	C vs. T	18.8	0.005	+0.1 (0.0)
				C vs. TB	25.0	0.003	+0.1 (0.0)
		Post-burn	2015 &/or 2016*	C vs. SpO	88.8	< 0.001	+0.3 (0.0)
				C vs. TB	208.7	< 0.001	+0.4 (0.0)
				SpBT vs. SpCR	22.9	0.003	-0.2 (0.0)

[1]Estimates given in terms of the second treatment relative to the first within contrast labels.
*Data from 2014 to 2016 at Land Between the Lakes were compiled as indicated to allow for contrasts among fires not conducted within the same year. Herbaceous fuels only monitored 2014-2016.

Appendix F. All interactions ($\alpha = 0.05$) between treatment and year effects on coarse (1000-, 100-, and 10- hour), fine (1-hour and litter), and herbaceous fuel-loading during (2008 to 2016) an oak woodland and savanna restoration experiment at 3 sites in the Mid-South. Interaction contrasts compared changes in fuel-loading across all available year intervals between: unmanaged or thinned (C vs. T), unmanaged or only burned in the fall (C vs. FaO) or spring (C vs. SpO), unmanaged or thinned and burned (C vs. TB), reduced to woodland (14 m^2 ha^{-1}) or savanna (7 m^2 ha^{-1}) residual basal area (W vs. S), burned in the fall or spring (Fa vs. Sp), and burned in separate spring fires (SpBT vs. SpCR). C vs. T was always tested, but other contrasts followed the implementation of involved management.

Site	Fuel category	Period	Interval[1]	Contrast	*F*	*p*	Estimate[1] Mg ha^{-1} (SE)
Catoosa WMA	Coarse	-	-	-	-	-	-
	Fine	Pre- to post- burn 1	2010 to 2011	C vs. TB	9.8	0.004	-2.6 (0.9)
	Herbaceous*	Pre- to post- burn 3	2014 to 2015	Fa vs. Sp	6.2	0.025	+0.4 (0.1)
Green River Game Lands	Coarse	Pre- to post- thin	2012 to 2014	C vs. T	4.6	0.033	+13.7 (6.4)
		Pre- to post- burn	2014 to 2015	C vs. TB	4.3	0.038	-13.0 (6.3)
				W vs. S	4.2	0.041	+12.0 (5.9)
	Fine	Pre- to post- thin	2012 to 2014	C vs. T	22.5	< 0.001	-2.2 (0.5)
		Pre- to post- burn	2014 to 2015	C vs. FaO	6.5	0.011	-1.6 (0.6)
		1 to 2 years post- burn	2015 to 2016	C vs. FaO	6.7	0.010	+1.8 (0.7)
				C vs. TB	6.5	0.011	+1.1 (0.5)
				W vs. S	19.1	< 0.001	-2.0 (0.5)
	Herbaceous*	Pre- to post- burn	2014 to 2015	W vs. S	6.2	0.014	+0.3 (0.1)
				Fa vs. Sp	22.2	< 0.001	+0.5 (0.1)
		1 to 2 years post- burn	2015 to 2016	C vs. TB	9.1	0.003	+0.5 (0.2)
				W vs. S	12.4	0.001	+0.7 (0.1)
Land Between the Lakes	Coarse	Pre- to post- thin	2009 to 2014	C vs. T	8.3	0.007	+28.1 (8.9)
	Fine	Pre- to post- burn	2014/2015 to 2015/2016*	C vs. SpO	6.0	0.021	-1.8 (0.8)
				C vs. TB	32.4	< 0.001	-2.6 (0.6)
				SpBT vs. SpCR	4.2	0.050	-0.3 (0.6)
	Herbaceous*	Pre- to post- burn	2014/2015 to 2015/2016*	C vs. SpO	30.1	< 0.001	+0.3 (0.1)
				C vs. TB	40.7	< 0.001	+0.2 (0.0)

[1]Estimates given in terms of the second treatment relative to the first within contrast label. *Data from 2014 to 2016 at Land Between the Lakes were compiled as indicated to allow for contrasts among fires not conducted within the same year. Herbaceous fuels only monitored 2014-2016.

Appendix G. Differences in the composition and/or density of shrubby, seedling, and sapling vegetation during oak woodland and savanna restoration experiments at Catoosa Wildlife Management Area (CWMA), Land Between the Lakes National Recreation Area (LBL), and Green River Game Lands (GRGL) as determined by restricted PERMANOVA (4,999 permutations). Significant Bonferroni adjusted *p*-values in bold (α = 0.05).

	Overall Tests:	Treatment				Period				Treatment × Period			
Site	Vegetation	*df*	*F*	*p*	R^2	*df*	*F*	*p*	R^2	*df*	*F*	*p*	R^2
CWMA	Shrubby	4, 85	9.04	**0.001**	0.30	4, 85	9.25	**0.001**	0.30	24, 65	6.58	**0.001**	0.71
	Seedlings	4, 85	6.60	**0.001**	0.24	4, 85	6.00	**0.001**	0.22	24, 65	3.50	**0.001**	0.56
	Saplings	4, 85	9.43	**0.001**	0.31	4, 85	4.61	**0.001**	0.18	24, 65	3.84	**0.003**	0.59
LBL	Shrubby	5, 66	2.97	**0.001**	0.18	2, 69	8.31	**0.001**	0.19	17, 54	3.22	**0.001**	0.50
	Seedlings	5, 66	1.94	**0.001**	0.13	2, 69	10.95	**0.001**	0.24	17, 54	2.62	**0.001**	0.45
	Saplings	5, 66	2.45	**0.001**	0.16	2, 69	8.41	**0.001**	0.20	17, 54	2.59	**0.001**	0.45
GRGL	Shrubby	5, 36	4.12	**0.001**	0.36	2, 39	3.78	**0.001**	0.16	17, 24	2.41	1.000	0.63
	Seedlings	5, 36	3.66	**0.001**	0.34	2, 39	2.03	**0.002**	0.09	17, 24	1.87	0.934	0.57
	Saplings	5, 36	4.27	**0.001**	0.37	2, 39	2.33	**0.002**	0.11	17, 24	2.61	0.110	0.65
	Treatment Contrasts[1]:	Control vs. Managed				Woodland vs. Savanna				Fall vs. Spring Fire			
		df	*F*	*p*	R^2	*df*	*F*	*p*	R^2	*df*	*F*	*p*	R^2
CWMA	Shrubby	1, 88	29.12	**0.001**	0.25	1, 70	2.88	**0.001**	0.04	1, 70	1.92	**0.013**	0.03
	Seedlings	1, 88	15.36	**0.001**	0.15	1, 70	1.76	**0.030**	0.02	1, 70	6.13	**0.001**	0.08
	Saplings	1, 88	22.46	**0.001**	0.20	1, 70	2.78	**0.002**	0.04	1, 70	4.81	**0.001**	0.06
LBL	Shrubby	1, 70	7.89	**0.001**	0.10	1, 46	2.66	**0.001**	0.05	-	-	-	-
	Seedlings	1, 70	5.74	**0.001**	0.08	1, 46	1.15	0.355	0.02	-	-	-	-
	Saplings	1, 70	6.62	**0.001**	0.09	1, 46	1.17	0.240	0.02	-	-	-	-
GRGL	Shrubby	1, 40	2.17	0.157	0.05	1, 26	5.80	**0.002**	0.18	1, 26	2.55	0.090	0.09
	Seedlings	1, 40	2.57	0.074	0.06	1, 26	3.09	**0.028**	0.11	1, 26	2.27	0.103	0.08
	Saplings	1, 40	3.61	**0.009**	0.08	1, 26	2.39	**0.024**	0.08	1, 26	1.54	0.222	0.06
	Period Contrasts[2]:	Pre-Management vs. Post-Cut				Post-Cut vs. Post-Fire				Post-Fire 1 vs. Post-Fire 2			
		df	*F*	*p*	R^2	*df*	*F*	*p*	R^2	*df*	*F*	*p*	R^2
CWMA	Shrubby	1, 28	10.53	**0.001**	0.27	1, 78	10.97	**0.001**	0.12	1, 38	2.27	**0.001**	0.06
	Seedlings	1, 28	7.52	**0.003**	0.21	1, 78	8.13	**0.001**	0.09	1, 38	1.17	0.284	0.03
	Saplings	1, 28	4.52	**0.002**	0.14	1, 78	6.97	**0.001**	0.08	1, 38	1.21	**0.006**	0.03
LBL	Shrubby	1, 50	14.35	**< 0.001**	0.24	1, 46	3.02	**0.001**	0.06	-	-	-	-
	Seedlings	1, 50	21.98	**< 0.001**	0.32	1, 46	3.21	**0.001**	0.07	-	-	-	-
	Saplings	1, 50	17.50	**< 0.001**	0.28	1, 46	2.99	**0.006**	0.06	-	-	-	-
GRGL	Shrubby	1, 28	4.67	**< 0.001**	0.14	1, 22	4.59	**0.001**	0.17	-	-	-	-
	Seedlings	1, 28	1.60	0.121	0.05	1, 22	1.46	0.164	0.06	-	-	-	-
	Saplings	1, 28	1.27	0.192	0.04	1, 22	1.72	**0.006**	0.07	-	-	-	-

[1]Tests of Control vs. burn-only at LBL and GRGL were never significant ($F < 6.72$, $p > 0.05$). Only spring fire was conducted at LBL. [2]Period contrasts at CWMA included post-fire 1 vs. post-fire 2 (presented) and post-fire 2 vs. post-fire 3. The latter was only significant for shrubby vegetation ($F = 4.39$, $p = 0.001$, $R^2 = 0.10$). Shrubby: multi-stemmed, woody and semi-woody (*e.g., Rubus* and *Smilax* spp.) species rarely >4 m tall and lianas. Seedlings: tree species (≥4 m in height at maturity) ≥30.5 cm tall but <1.4 m tall. Saplings: trees ≥1.4 m tall and <7.6 cm diameter at breast height.

Appendix H. Multivariate homogeneity of variance dispersions across treatments and periods during oak woodland and savanna restoration experiments at Catoosa Wildlife Management Area (CWMA), Land Between the Lakes National Recreation Area (LBL), and Green River Game Lands (GRGL). Bold indicates significance and lowercase letters depict differences as determined by Tukey mean separation (α = 0.05 for both). Commonly observed differences by period are presented. Only sapling community dispersion at CWMA differed by treatment (Control: 0.14 b, SpW: 0.20 ab, FaW: 0.19 ab, FaS: 0.21 a, SpS: 0.21 a).

		Treatment Groups			Period Groups			Dispersion estimates by period				
Site	Vegetation[1]	*df*	*F*	*p*	*df*	*F*	*p*	Pre-Mng	Post-Cut	Post-Fire (1)	Post-Fire 2	Post-Fire 3
CWMA	Shrubby	4, 85	0.68	0.617	4, 85	4.13	**0.004**	0.07 b	0.18 a	0.20 a	0.19 a	0.21 a
	Seedlings	4, 85	0.78	0.540	4, 85	13.75	< **0.001**	0.06 c	0.13 b	0.18 a	0.17 ab	0.19 a
	Saplings	4, 85	3.36	**0.013**	4, 85	18.19	< **0.001**	0.09 c	0.16 b	0.24 a	0.25 a	0.22 a
LBL	Shrubby	5, 66	1.83	0.119	2, 69	25.37	< **0.001**	0.09 b	0.23 a	0.28 a	-	-
	Seedlings	5, 66	0.73	0.606	2, 69	103.91	< **0.001**	0.08 c	0.22 b	0.25 a	-	-
	Saplings	5, 66	0.30	0.911	2, 69	56.61	< **0.001**	0.09 b	0.25 a	0.28 a	-	-
GRGL	Shrubby	5, 36	0.54	0.745	2, 39	0.94	0.399	0.31 a	0.32 a	0.27 a	-	-
	Seedlings	5, 36	0.48	0.791	2, 39	2.78	0.074	0.24 a	0.22 a	0.16 a	-	-
	Saplings	5, 36	2.54	0.054	2, 39	0.64	0.531	0.19 a	0.21 a	0.21 a	-	-

[1]Shrubby vegetation included multi-stemmed woody and semi-woody (e.g., *Smilax* and *Rubus* spp.) species rarely >4 m tall and lianas. Seedlings (≥30.5 cm tall but <1.4 m tall) and Saplings (≥1.4 m tall and <7.6 cm diameter at breast height) were tree species ≥4 m in height at maturity. Treatments referenced in table include unmanaged oak forests (Control) and savanna (7 m^2 ha^{-1}, S) and woodland (14 m^2 ha^{-1}, W) residual basal area stands burned in the spring (Sp) or fall (Fa). Period associations were prior to management (Pre-Mng), after canopy disturbance (Post-Cut), or after prescribed fires (Post-Fire, multiple at Catoosa).

Appendix I1. Shrubby vegetation significantly indicative of treatments and periods within restoration. Treatments were unmanaged oak forests (C), savanna residual basal area (7 m^2 ha^{-1}, S), woodland residual basal area (14 m^2 ha^{-1}, W), spring burned stands (Sp), fall burned stands (Fa), or thinned and/or burned stands (M). Period associations were pre-management (PM), post-cut (PC), or post-fire (PF, multiple at Catoosa). Specificity (A), sensitivity (B), indicator value (IndVal), and *p*-values (4,999 permutations) are presented.

Catoosa Wildlife Management Area						Land Between the Lakes National Recreation Area						Green River Game Lands					
Species	Trt	*A*	*B*	Ind Val	*p*	Species	Trt	*A*	*B*	Ind Val	*p*	Species	Trt	*A*	*B*	Ind Val	*p*
Treatment																	
KALA	C	0.96	0.09	0.08	0.003	VIRO	W	0.48	0.64	0.31	0.001	PAQU	W	0.99	0.16	0.16	0.001
						RUAR	W	0.47	0.44	0.21	0.011	SMRO	W	0.77	0.26	0.19	0.001
RUFL	S	0.81	0.20	0.16	< 0.001	VAAR	W	0.51	0.16	0.08	0.025	TORA	W	0.97	0.09	0.09	0.013
TORA	S	0.68	0.05	0.04	0.002	ARSP	W	0.88	0.19	0.17	< 0.001	VIRO	W	0.73	0.21	0.16	0.012
VICI	S	0.79	0.05	0.04	< 0.001	LOJA	W	0.57	0.08	0.05	0.009	VICI	W	0.89	0.17	0.15	< 0.001
RUFL	Sp	0.60	0.14	0.08	0.004	VACC	S	0.68	0.44	0.30	< 0.001	VACC	S	0.81	0.7	0.56	< 0.001
						TORA	S	0.76	0.34	0.26	< 0.001	KALA	S	0.82	0.5	0.41	0.001
RHCA	Fa	0.66	0.06	0.04	0.007	RHCO	S	0.56	0.31	0.18	0.003	RHMA	S	0.75	0.11	0.08	0.013
						SMGL	S	0.50	0.27	0.14	0.014						
VACC	M	0.88	0.76	0.66	< 0.001	PAQU	S	0.65	0.25	0.16	0.001						
RUAR	M	0.99	0.57	0.58	< 0.001	RUFL	S	0.65	0.19	0.12	0.002						
SMRO	M	0.87	0.39	0.34	0.009	VICI	S	0.52	0.17	0.08	0.011						
SMGL	M	0.94	0.45	0.42	0.002												
RHCO	M	0.99	0.18	0.18	< 0.001												
VIRO	M	0.81	0.15	0.10	< 0.001												
Period																	
SMTA	PC	0.93	0.06	0.06	< 0.001	VIRO	PC	0.64	0.80	0.50	< 0.001	RHMA	PC	0.93	0.22	0.20	< 0.001
						VACC	PC	0.54	0.47	0.26	< 0.001	SMRO	PC	0.45	0.25	0.12	0.042
VACC	PF1	0.26	0.89	0.23	0.002	RUAR	PC	0.48	0.45	0.21	0.020	RHCA	PC	0.82	0.07	0.05	0.003
SMGL	PF1	0.43	0.67	0.29	< 0.001	TORA	PC	0.72	0.37	0.26	0.001						
VIRO	PF1	0.28	0.19	0.05	0.045	SMRO	PC	0.56	0.33	0.18	< 0.001	RUAR	PF	0.89	0.52	0.46	0.001
RUFL	PF1	0.47	0.20	0.10	0.001	PAQU	PC	0.62	0.30	0.18	< 0.001	SMGL	PF	0.51	0.28	0.14	0.026
						VAAR	PC	0.65	0.18	0.12	0.012	VIRO	PF	0.52	0.19	0.10	0.016
SMRO	PF2	0.28	0.50	0.14	0.001	RUFL	PC	0.52	0.20	0.10	0.015	RUFL	PF	0.94	0.11	0.10	0.004
VAAR	PF2	0.76	0.08	0.06	< 0.001	SYOR	PC	0.54	0.13	0.07	0.008						
RHCA	PF2	0.40	0.10	0.04	0.002	VICI	PC	0.79	0.20	0.16	< 0.001						
						ARSP	PC	0.64	0.19	0.12	0.039						
RUAR	PF3	0.38	0.66	0.25	< 0.001												
RHCO	PF3	0.54	0.29	0.16	< 0.001	RHCO	PF	0.73	0.35	0.26	0.001						
GABA	PF3	0.99	0.11	0.11	< 0.001												

[1]Shrubby vegetation included multi-stemmed woody and semi-woody (e.g., *Smilax* and *Rubus* spp.) species rarely >4 m tall and lianas. Species codes are the first two letters of genus and species. All *Vaccinium* spp. except *Vaccinium arboreum* were aggregated (VACC). All species ≥1% of total density at ≥10% of stands within a year were tested. Species not indicative of a treatment ($p > 0.05$) included: SMRO and SYOR at LBL, and RUAR, SMGL, RUFL, and COAM at GRGL. Species not indicative of any period ($p > 0.05$) included: VICI at CWMA, SMGL and LOJA at LBL, and VACC, KALA, PAQU, CAFL, and VICI at GRGL. Within treatments and periods, species are in descending order of overall mean density (stems ha^{-1}).

Appendix I2. Seedling species determined to be significant indicators of treatments and periods within restoration. Treatments were unmanaged oak forests (C), savanna residual basal area (7 m^2 ha^{-1}, S), woodland residual basal area (14 m^2 ha^{-1}, W), spring burned stands (Sp), fall burned stands (Fa), or thinned and/or burned stands (M). Period associations were pre-management (PM), post-cut (PC), or post-fire (PF, multiple at Catoosa). Specificity (A), sensitivity (B), indicator value (IndVal), and *p*-values (4,999 permutations) are presented.

Catoosa Wildlife Management Area						Land Between the Lakes National Recreation Area						Green River Game Lands					
Species	Trt	*A*	*B*	Ind Val	*p*	Species	Trt	*A*	*B*	Ind Val	*p*	Species	Trt	*A*	*B*	Ind Val	*p*
Treatment																	
PIST	C	0.81	0.26	0.21	< 0.001	FRPE	C	0.80	0.29	0.23	0.002	ACRU	W	0.64	0.77	0.50	0.002
QUMO	C	0.52	0.07	0.04	0.025	OSVI	C	0.84	0.40	0.34	< 0.001	LITU	W	0.81	0.52	0.42	< 0.001
OSVI	C	0.84	0.05	0.04	0.005	ASTR	C	0.85	0.11	0.10	0.030	QUAL	W	0.72	0.50	0.36	0.002
FAGR	C	0.85	0.08	0.07	< 0.001	ULAM	C	0.87	0.13	0.12	0.031	QURU	W	0.64	0.35	0.22	0.019
						FAGR	C	0.88	0.15	0.13	< 0.001	CARYA	W	0.82	0.38	0.31	0.001
QUAL	Sp	0.54	0.32	0.18	0.015							PRSE	W	0.92	0.28	0.25	< 0.001
CARYA	Sp	0.43	0.26	0.12	0.003	QUAL	M	0.75	0.49	0.37	< 0.001	MAAC	W	0.94	0.12	0.12	0.011
COFL	Sp	0.56	0.13	0.07	< 0.001	NYSY	M	0.81	0.40	0.32	< 0.001	COFL	W	0.84	0.12	0.10	0.013
LIST	Sp	0.91	0.10	0.09	< 0.001	QUCO	M	0.83	0.21	0.17	0.001	HACA	W	0.89	0.06	0.05	0.028
PRSE	Sp	0.68	0.09	0.06	< 0.001	SAAL	M	0.73	0.48	0.35	< 0.001						
						QUST	M	0.99	0.11	0.11	0.001	SAAL	S	0.66	0.41	0.27	0.039
LITU	Fa	0.82	0.09	0.07	0.005	QUFA	M	0.84	0.16	0.14	0.003						
						QUMO	M	0.92	0.31	0.29	0.002						
ACRU	M	0.85	0.86	0.72	0.007	PRSE	M	0.90	0.28	0.25	< 0.001						
SAAL	M	0.99	0.70	0.69	< 0.001	QUVE	M	0.67	0.39	0.26	0.002						
NYSY	M	0.96	0.40	0.38	< 0.001	LITU	M	0.89	0.10	0.09	0.044						
OXAR	M	0.97	0.32	0.31	< 0.001	DIVI	M	0.99	0.09	0.10	0.008						
QUCO	M	0.90	0.31	0.28	0.001	LIST	M	0.91	0.11	0.10	0.006						
QUVE	M	0.91	0.29	0.26	< 0.001												
QUFA	M	0.95	0.16	0.15	< 0.001												
Period																	
QUCO	PC	0.47	0.30	0.14	0.033	FRAM	PM	0.8	0.09	0.08	0.044	QUVE	PC	0.43	0.33	0.14	0.046
COFL	PC	0.52	0.13	0.07	0.044							MAFR	PC	0.71	0.08	0.06	0.026
PIVI	PC	0.79	0.06	0.05	0.002	QUAL	PC	0.52	0.64	0.32	< 0.001						
						NYSY	PC	0.52	0.54	0.28	< 0.001	ACRU	PF	0.41	0.81	0.34	0.023
ACRU	PF	0.45	0.93	0.42	< 0.001	ULAL	PC	0.39	0.35	0.14	0.018	LITU	PF	0.55	0.68	0.37	0.016
SAAL	PF	0.54	0.69	0.37	< 0.001	SAAL	PC	0.46	0.61	0.28	< 0.001	QUAL	PF	0.47	0.57	0.26	0.005
NYSY	PF	0.65	0.43	0.28	< 0.001	QUST	PC	0.55	0.2	0.11	0.007	QUCO	PF	0.45	0.51	0.23	0.006
QUAL	PF	0.55	0.32	0.18	< 0.001	QUFA	PC	0.59	0.25	0.14	0.014	QURU	PF	0.48	0.42	0.20	0.007
OXAR	PF	0.77	0.35	0.27	< 0.001	CARYA	PC	0.52	0.65	0.34	< 0.001	NYSY	PF	0.63	0.49	0.30	0.004
QUVE	PF	0.48	0.30	0.14	0.004	QUMO	PC	0.63	0.44	0.27	< 0.001	OXAR	PF	0.58	0.30	0.18	0.008
CARYA	PF	0.58	0.29	0.17	< 0.001	PRSE	PC	0.57	0.42	0.24	< 0.001	ROPS	PF	0.61	0.33	0.20	0.009
LIST	PF	0.78	0.06	0.05	0.002	ACRU	PC	0.66	0.19	0.12	< 0.001	PRSE	PF	0.44	0.21	0.09	0.021
AMAR	PF	0.48	0.08	0.04	0.028	QUVE	PC	0.49	0.58	0.28	< 0.001	AIAL	PF	0.60	0.32	0.19	0.040
PRSE	PF	0.63	0.07	0.04	0.002	LITU	PC	0.58	0.14	0.08	< 0.001						
QURU	PF	0.79	0.09	0.07	0.001	AMAR	PC	0.52	0.23	0.12	< 0.001						
						DIVI	PC	0.56	0.17	0.10	0.019						
						QURU	PC	0.51	0.21	0.11	0.005						
						OXAR	PC	0.6	0.25	0.15	< 0.001						
						LIST	PC	0.52	0.19	0.10	0.004						
						ULAM	PC	0.89	0.16	0.14	< 0.001						
						FAGR	PC	0.5	0.06	0.03	0.007						
						CECA	PC	0.55	0.07	0.04	0.026						
						COFL	PF	0.63	0.11	0.07	0.020						
						FRPE	PF	0.54	0.27	0.14	0.028						
						OSVI	PF	0.57	0.31	0.18	0.001						

[1]Seedlings defined as tree species (≥4 m in height at maturity) ≥30.5 cm tall but <1.4 m tall. Species codes are the first two letters of genus and species. All hickories were aggregated (CARYA). All species ≥1% of total density at ≥10% of stands within a year were tested. Species not indicative of any treatment ($p > 0.05$) included: AMAR and QURU at CWMA, ULAL, CARYA, FRAM, ACRU, COFL, AMAR, QURU, QUMA, OXAR, and CECA at LBL, and QUVE, NYSY, OXAR, AIAL, MAFR, QUCO, and ROPS at GRGL. Species not indicative of a period ($p > 0.05$) included: PIST, QUFA, and LITU at CWMA, QUCO, QUMA, and ASTR at LBL, and MAAC, SAAL, QUMO, CARYA, and COFL at GRGL. Within treatments and periods, species in descending order of overall mean density (stems ha^{-1}).

Appendix I3. Sapling species determined to be significant indicators of treatments and periods within restoration. Treatments were unmanaged oak forests (C), savanna residual basal area (7 m^2 ha^{-1}, S), woodland residual basal area (14 m^2 ha^{-1}, W), spring burned stands (Sp), fall burned stands (Fa), or thinned and/or burned stands (M). Period associations were pre-management (PM), post-cut (PC), or post-fire (PF, multiple at Catoosa). Specificity (A), sensitivity (B), indicator value (IndVal), and *p*-values (4,999 permutations) are presented.

Catoosa Wildlife Management Area						Land Between the Lakes National Recreation Area						Green River Game Lands					
Species	Trt	*A*	*B*	Ind Val	*p*	Species	Trt	*A*	*B*	Ind Val	*p*	Species	Trt	*A*	*B*	Ind Val	*p*
Treatment																	
PIST	C	0.88	0.92	0.81	< 0.001	OSVI	C	0.77	0.59	0.45	< 0.001	CADE	C	0.59	0.24	0.14	0.007
FAGR	C	0.58	0.23	0.13	< 0.001	ULAL	C	0.71	0.47	0.34	0.023						
ILOP	C	0.43	0.18	0.08	0.002	FAGR	C	0.92	0.67	0.61	< 0.001	LITU	W	0.71	0.67	0.48	< 0.001
						ASTR	C	0.83	0.14	0.12	0.004	CARYA	W	0.64	0.26	0.17	0.018
COFL	W	0.60	0.34	0.20	0.006	ACSA	C	0.95	0.53	0.50	< 0.001	PRSE	W	0.89	0.45	0.40	< 0.001
						ULAM	C	0.89	0.19	0.17	0.040	QUAL	W	0.63	0.43	0.27	< 0.001
LITU	S	0.93	0.10	0.10	< 0.001	FRPE	C	0.75	0.28	0.21	0.010	QURU	W	0.53	0.37	0.19	0.008
QUAL	S	0.83	0.28	0.23	< 0.001	COFL	C	0.68	0.28	0.19	0.027	AIAL	W	0.79	0.20	0.16	0.014
PRSE	S	0.89	0.17	0.14	< 0.001	ACRU	C	0.81	0.24	0.19	0.034	MAAC	W	0.68	0.30	0.21	0.008
QUCO	S	0.81	0.30	0.24	< 0.001							PIST	W	0.71	0.40	0.28	< 0.001
QUFA	S	0.63	0.18	0.12	< 0.001	QUMO	M	0.95	0.38	0.36	< 0.001	HACA	W	0.87	0.17	0.14	0.002
						NYSY	M	0.76	0.56	0.42	< 0.001	HAVI	W	0.54	0.07	0.04	0.036
LITU	Fa	0.93	0.10	0.10	< 0.001	OXAR	M	0.78	0.41	0.31	0.001						
ASTR	Fa	0.74	0.05	0.04	< 0.001	CARYA	M	0.67	0.49	0.32	0.007	QUMO	S	0.59	0.60	0.35	0.001
						QUVE	M	0.66	0.48	0.31	0.007	QUCO	S	0.54	0.36	0.19	0.004
QUAL	Sp	0.81	0.24	0.19	0.002	SAAL	M	0.85	0.43	0.37	< 0.001	TSCA	S	0.54	0.06	0.03	0.035
PRSE	Sp	0.85	0.16	0.13	< 0.001	QUAL	M	0.69	0.42	0.29	0.002						
LIST	Sp	0.96	0.20	0.19	< 0.001	PRSE	M	0.83	0.43	0.36	< 0.001	ACRU	M	0.98	0.87	0.85	< 0.001
QUCO	Sp	0.77	0.26	0.20	< 0.001	QUCO	M	0.94	0.30	0.28	< 0.001	OXAR	M	0.94	0.67	0.64	0.001
QUFA	Sp	0.76	0.21	0.16	< 0.001	AMAR	M	0.71	0.24	0.17	0.019	ROPS	M	0.93	0.26	0.24	0.002
COFL	Sp	0.66	0.38	0.25	< 0.001	QUFA	M	0.97	0.20	0.19	0.001						
						QURU	M	0.63	0.21	0.13	0.032						
ACRU	M	0.87	0.89	0.77	0.006	QUST	M	0.91	0.18	0.17	0.001						
OXAR	M	0.90	0.72	0.64	0.007	DIVI	M	0.96	0.12	0.11	0.008						
SAAL	M	0.99	0.51	0.50	< 0.001												
CARYA	M	0.94	0.21	0.19	0.002												
QUVE	M	0.97	0.24	0.23	< 0.001												
Period																	
PIST	PC	0.34	0.44	0.15	0.018	FRAM	PM	0.85	0.11	0.10	0.003	PIST	PM	0.64	0.28	0.18	0.014
FAGR	PC	0.59	0.12	0.07	0.004							COFL	PM	0.46	0.34	0.16	0.011
ASTR	PC	0.70	0.06	0.04	0.009	QUMO	PC	0.59	0.46	0.27	0.001	TSCA	PM	0.72	0.06	0.04	0.002
PIVI	PC	0.57	0.07	0.04	0.012	NYSY	PC	0.41	0.68	0.27	0.022						
						OXAR	PC	0.49	0.53	0.26	0.001	CARYA	PC	0.46	0.37	0.17	0.023
ACRU	PF2-3	0.55	0.96	0.53	< 0.001	CARYA	PC	0.42	0.63	0.26	0.010	MAFR	PC	0.49	0.23	0.12	0.040
OXAR	PF2-3	0.61	0.86	0.52	< 0.001	QUVE	PC	0.50	0.64	0.32	0.001						
SAAL	PF2-3	0.60	0.54	0.32	< 0.001	SAAL	PC	0.46	0.51	0.24	0.015	ACRU	PF	0.47	0.82	0.38	0.037
LITU	PF2-3	0.88	0.09	0.08	0.015	QUAL	PC	0.53	0.54	0.28	0.001	LITU	PF	0.58	0.64	0.37	0.002
QUAL	PF2-3	0.73	0.25	0.18	0.001	PRSE	PC	0.57	0.58	0.34	< 0.001	NYSY	PF	0.54	0.66	0.36	0.025
QUVE	PF2-3	0.52	0.24	0.12	0.013	LIST	PC	0.51	0.35	0.18	0.008	QUMO	PF	0.53	0.57	0.30	0.005
PRSE	PF2-3	0.79	0.13	0.10	0.004	ULAM	PC	0.81	0.26	0.20	0.001	SAAL	PF	0.60	0.57	0.34	0.001
LIST	PF2-3	0.73	0.15	0.11	0.002	QUCO	PC	0.63	0.37	0.23	0.011	PRSE	PF	0.71	0.33	0.24	0.010
QUCO	PF2-3	0.84	0.27	0.23	< 0.001	AMAR	PC	0.41	0.31	0.12	0.039	QUCO	PF	0.63	0.40	0.25	0.005
QUFA	PF2-3	0.77	0.19	0.14	< 0.001	ACRU	PC	0.6	0.26	0.15	0.006	QUAL	PF	0.45	0.34	0.15	0.017
						QUST	PC	0.61	0.27	0.17	0.005	ROPS	PF	0.76	0.47	0.36	0.001
						DIVI	PC	0.74	0.18	0.13	0.024	QURU	PF	0.55	0.42	0.23	0.002
						CECA	PC	0.56	0.17	0.10	0.022	AIAL	PF	0.73	0.23	0.17	0.031
						OSVI	PF	0.53	0.5	0.26	0.022						
						FRPE	PF	0.61	0.32	0.19	0.031						

[1]Saplings defined as tree species (≥4 m in height at maturity) ≥1.4 m tall and <7.6 cm diameter at breast height. Species codes are the first two letters of genus and species. All hickories were aggregated (CARYA). All species ≥1% of total density at ≥10% of stands within a year were tested. Species not indicative of a treatment ($p > 0.05$) included: NYSY and LIST at CWMA, FRAM, JUVI, LITU, LIST, and CECA at LBL, and FRPE, NYSY, SAAL, QUVE, COFL, MAMA, and MAFR at GRGL. Species not indicative of a period ($p > 0.05$) included: ILOP, NYSY, CARYA, and COFL at CWMA, QUMA, ULRU, ULAL, COFL, QUFA, QURU, JUVI, LITU, FAGR, ASTR, and ACSA at LBL, and HACA, CADE, MAMA, OXAR, QUVE, FRPE, and MAAC at GRGL. Within treatments and periods, species in descending order of overall mean density (stems ha^{-1}).

Appendix J. ANCOVA/ANOVA model results for percent groundcover variables during (2008 to 2016) point intercept monitoring of oak woodland and savanna restoration experiments at Catoosa Wildlife Management Area (Cumberland County, TN), Green River Game Lands (Polk County, NC), and Land Between the Lakes National Recreation Area (Stewart County, TN).

Site	Groundcover variable	Treatment *F*	Treatment *p*	Year *F*	Year *p*	Treatment × Year *F*	Treatment × Year *p*
Catoosa Wildlife Management Area	Graminoid	2.2	0.203	25.6	< 0.001	6.8	**< 0.001**
	Forb	4.4	0.062	34.4	< 0.001	6.3	**< 0.001**
	Richness	3.1	0.120	22.9	< 0.001	6.6	**< 0.001**
	Diversity	3.8	0.086	24.5	< 0.001	5.0	**< 0.001**
	Woody	17.6	0.002	132.4	< 0.001	8.9	**< 0.001**
	Litter	30.9	0.001	15.7	< 0.001	3.3	**< 0.001**
	Debris	0.3	0.879	26.8	< 0.001	4.1	**< 0.001**
	Bare	11.5	0.007	13.4	< 0.001	4.5	**< 0.001**
Green River Game Lands	Graminoid	31.2	< 0.001	67.6	< 0.001	14.3	**< 0.001**
	Forb	10.0	< 0.001	21.8	< 0.001	4.2	**< 0.001**
	Richness	20.5	< 0.001	45.3	< 0.001	7.2	**< 0.001**
	Diversity	30.3	< 0.001	50.8	< 0.001	8.7	**< 0.001**
	Woody	21.4	< 0.001	9.0	< 0.001	8.6	**< 0.001**
	Litter	28.4	< 0.001	60.6	< 0.001	8.5	**< 0.001**
	Debris	7.1	< 0.001	12.4	< 0.001	3.7	**< 0.001**
	Bare	17.6	< 0.001	57.0	< 0.001	6.8	**< 0.001**
Land Between the Lakes	Graminoid	7.4	0.011	10.2	< 0.001	5.2	**< 0.001**
	Forb	0.6	0.612	17.3	< 0.001	2.7	**0.001**
	Richness	2.6	0.123	20.0	< 0.001	5.4	**< 0.001**
	Diversity	2.8	0.109	19.9	< 0.001	4.8	**< 0.001**
	Woody	5.8	0.020	68.3	< 0.001	5.7	**< 0.001**
	Litter	41.0	< 0.001	10.9	< 0.001	5.4	**< 0.001**
	Debris	12.7	0.003	12.6	**< 0.001**	1.6	0.069
	Bare	6.3	0.016	31.3	< 0.001	3.9	**< 0.001**

Richness and diversity (Shannon-Wiener Index) refer to the herbaceous community. Bold indicates significant ($\alpha = 0.05$) and interpretable effects. Model *df* calculated using Kenward Rogers adjustment.

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